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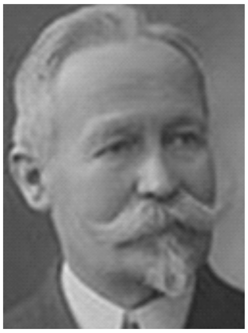
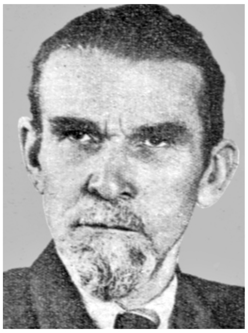


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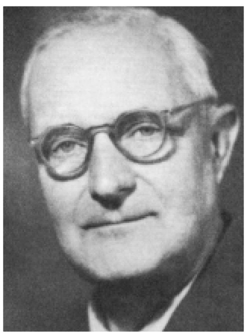


Special Issue

The International Union of Geodesy and Geophysics: from different spheres to a common globe

Editors: A. Ismail-Zadeh and J. A. Joselyn

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IUGG-personalities on the cover page

From top left to bottom right:

Charles Jean-Pierre Lallemand (France, 1857–1938): Founding President of IUGG (1919–1933), made significant contributions to determination of precise heights above mean sea level.

Antoni Boleslaw Dobrowolski (Poland, 1872–1954): Vice-President of the IAHS Glacier Commission, introduced the concept of the cryosphere and proposed the establishment of a single "association of cryology" within IUGG in 1936.

James Clement Dooge (Ireland, 1922–2010): IAHS President (1975–1979) and IUGG Bureau Member (1979–1987), Irish politician, one of the founding fathers of modern hydrology.

Kalpathi Ramakrishna Ramanathan (India, 1893–1984): IAMAS President (1951–1954), IUGG President (1954–1957), made numerous contributions to studies of atmospheric ozone, monsoonal patterns, and solar and atmospheric radiation.

Wallace Smith Broecker (USA, 1931–2019): Made significant contributions to the concept of a global oceanic "conveyor belt" of currents that transports heat around the Earth.

Felix Andries Vening Meinesz (the Netherlands, 1887–1966): IAG President (1933–1945), IUGG President (1948–1951), made outstanding contributions to pendulum gravity measurements, in particular, on sea.

Valeriia Alekseevna Troitskaya (Russia/Australia, 1917–2010): IUGG Bureau Member (1963–1967), IAGA President (1971–1975), made important contributions to the description of geomagnetic micro-pulsations and ULF waves.

Beno Gutenberg (Germany/USA, 1889–1960): IASPEI President (1952–1954), made significant contributions to studies of seismic waves, earthquake magnitudes/energy, and the physical properties of the Earth's interior.

George Patrick Leonard Walker (UK, 1926–2005): Made outstanding contributions to mineralogy and volcanology.

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Open Access History of Geo- and Space Sciences

Preface to the special issue "The International Union of Geodesy and Geophysics: from different spheres to a common globe"

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Many environmental challenges facing society since the last century require international solutions. Examples include exploration of the Earth and its environment in space; exploration of our rivers, oceans, and atmosphere; climate change; securing clean water and energy; and understanding and mitigating disasters due to natural hazard events. Earth and space sciences lie at the heart of these challenges and occupy a central role in international agendas.

The International Union of Geodesy and Geophysics (IUGG) has been coordinating and promoting international efforts in Earth and space sciences since 1919. Under IUGG's umbrella, eight international scientific associations and several interdisciplinary bodies cover many disciplines of geo- and space sciences and promote research of the Earth from its core and its space environment up to the Sun. Thousands of scientists from many nations and specific scientific disciplines have developed ways of cooperation through IUGG's international associations and learned how to work together to promote geosciences. IUGG has been initiating, developing, and implementing international cooperative programs; setting scientific standards; developing research tools; educating and building capacity; and contributing to science for policy and science diplomacy.

The purpose of this special issue (SI) is not to relay a definitive history of the development of international cooperation in the geosciences, but to summarize IUGG's remarkable role during the 100-year span of its existence. The first part of the SI "The union: bringing together geophysical disciplines" begins with the present overview of the IUGG mission and structure, and the circumstances of its founding and early development are presented up to the beginning of World War II. The second article starts with recovery after World War II and addresses the years of extraordinary development of geophysical science through the International Geophysical Year (IGY; 1957–1958) and the concurrent evolution of IUGG structure and programs extending up to the General Assembly of 1999. The rapid advances that have occurred thus far into the 21st century are reviewed in the third article, and foresights on IUGG future development conclude this first part of the SI. Outstanding histories of each of the IUGG associations are then told.

The second part of the SI "Around the earth: glaciers, rivers, air, and oceans" presents articles about the histories of the International Association of Cryospheric Sciences (*IACS: past, present, and future of the International Association of Cryospheric Sciences*), the International Association of Hydrological Sciences (*IAHS: a brief history of hydrology*), the International Association of Meteorology and Atmospheric Sciences (*IAMAS: a century of international cooperation in atmospheric sciences*), and the International Association for the Physical Sciences of the Oceans (*IAPSO: tales from the ocean frontier*).

The third part of the SI "Within and on the earth: gravity, magnets, earthquakes, and volcanoes" presents articles about the histories of the International Association of Geodesy (*The International Association of Geodesy: from an ideal sphere to an irregular body subjected to global change*), the International Association of Geomagnetism and Aeronomy

(*IAGA: a major role in understanding our magnetic planet*), the International Association of Seismology and Physics of the Earth's Interior (*IASPEI: its origins and the promotion of global seismology*), and the International Association of Volcanology and Chemistry of the Earth's Interior (*IAVCEI: from small beginnings to a vibrant international association*).

This volume, proposed in 2014 by the IUGG Bureau, is the combined effort of a number of authors and advisors, including past and current IUGG and association officers. We are grateful to Franz Kuglitsch and Katina Rogers Roopchansingh for their technical and editorial assistance, to Hans Volkert for proposing the title of this SI and editorial support, and to reviewers for their constructive comments and suggestions for revision of the initial manuscripts of the papers published in the SI. The IUGG archives, curated by the American Institute of Physics Center for the History of Physics (Gregory Good, director), located in College Park, MD, USA, were heavily consulted in preparation for this SI, and we acknowledge their helpful staff. We are very thankful to Kristian Schlegel, HGSS editor-in-chief, for his enthusiastic efforts and assistance in producing the SI.

Jo Ann Joselyn and Alik Ismail-Zadeh
SI Editors

Appendix A: List of acronyms

AfSC	African Seismological Commission
AGU	American Geophysical Union
AI	artificial intelligence
AK1345	seismic travel-time model, without special meaning
AMS	Army Map Service
AOGS	Asia Oceania Geosciences Society
ASC	Asian Seismological Commission
BAS	British Antarctic Survey
BCE or BC	Before Common Era
BGI	Bureau Gravimétrique International
BHI	Bureau International de l'Heure
BIPM	Bureau International des Poids et Mesures
BV	Bulletin Volcanologique (Bulletin of Volcanology)
CAST	China Association for Science and Technology
CCEC	Commission on Climatic and Environmental Change (IUGG)
CCTF	Consultative Committee for Time and Frequency
CFC	chlorofluorocarbon
CIESM	Commission Internationale pour l'Exploration Scientifique de la mer Méditerranée
CIG	Comite Internationale de Geophysique
CIG	Commission Internationale des Glaciers
CliC	Climate and Cryosphere project (WCRP)
CME	coronal mass ejection
CMG	Commission on Mathematical Geophysics (IUGG)
CMIP	Coupled Model Intercomparison Project
CMSLT	Commission on Mean Sea Level and Tides
CNAA	Committee on Nucleation and Atmospheric Aerosols (of ICCP)
CNES	Centre National d'Etudes Spatiales, France
CO_2	carbon dioxide
CODATA	Committee on Data for Science and Technology
COSPAR	Committee on Space Research
COSTED	Committee on Science and Technology in Developing Countries
CoV	Cities on Volcanoes
COWAR	Committee on Water Research
CRCM	Commission on Recent Crustal Movements
CSAGI	Committee for the International Geophysical Year
CSR	Committee on Space Research (IUGG)
CSTG	Coordination of Space Techniques for Geodesy and Geodynamics
CTBT	Comprehensive Nuclear-Test-Ban Treaty
DACA-13	Davos Atmosphere and Cryosphere Assembly, 2013
DC	District of Columbia
DFG	German Research Foundation
DMI	Danish Meteorological Institute
DOES	Deep Ocean Exchange with the Shelf
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EC	Executive Committee
ECR	early career researcher
ECS	early career scientist
ECV	essential climate variable
ED50	European Datum 1950
EGIG	Expédition Glaciologique Internationale au Groenland 1957–1960
eGY	electronic Geophysical Year
EMSEV	Inter-Association Working Group on Electromagnetic Studies of Earthquakes and Volcanoes

ENHANS	Extreme Natural Hazards and Societal Implications
ENSO	El Niño–Southern Oscillation
EOS-80	International Equation of State of Seawater – 1980
EOST	Ecole et Observatoire des Sciences de la Terre, Strasbourg
ESA	European Space Agency
ESC	European Seismological Commission
ESM	Earth System Model
FAGS	Federation of Astronomical and Geophysical Data Analysis Services
FAO	The Food and Agriculture Organization of the United Nations
FDSN	International Federation of Digital Seismograph Networks
FIG	Fédération Internationale de Géomètres
FRG	Federal Republic of Germany
G7	Group of Seven countries: Canada, France, Germany, Italy, Japan, UK, and USA
GA	general assembly
GAPHAZ	Glacier and Permafrost Hazards in Mountains standing group (IACS & IPA)
GARP	Global Atmospheric Research Program
GCOS	Global Climate Observing System
GDP	International Geodynamics Project
GDR	German Democratic Republic
GEBCO	General Bathymetric Chart of the Oceans
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GEWEX	Global Energy and Water Exchanges project (WCRP)
GFZ	German Research Centre for Geosciences
GGOS	Global Geodetic Observing System
GGRF	Global Geodetic Reference Frame
GGP	Global Geodynamics Project
GIS	Geographic Information System
GLASS	GEWEX Land Atmosphere System Study
GLIMS	Global Land Ice Measurements from Space initiative
GLOF	glacier lake outburst flood
GLOSS	Global Sea Level Observing System
GNSS	Global Navigation Satellite Systems
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GRC	Commission on Geophysical Risk and Sustainability (IUGG)
GRS 67	Geodetic Reference System 1967
GRS 80	Geodetic Reference System 1980
GRACE	Gravity Recovery And Climate Experiment
GTN-G	Global Terrestrial Network for Glaciers (GCOS)
GVP	Global Volcanism Program (SI)
HMS	His/Her Majesty's Ship
HMSH	His Most Serene Highness
HSJ	Hydrological Sciences Journal (IAHS)
IABO	International Association for Biological Oceanography
IACS	International Association of Cryospheric Sciences (IUGG)
IAG	International Association of Geodesy (IUGG)
IAGA	International Association of Geomagnetism and Aeronomy (IUGG)
IAGC	International Association of Geochemistry and Cosmochemistry
IAGP	International Antarctic Glaciological Project
IAHR	International Association of Hydraulic Research
IAHS	International Association of Hydrological Sciences (IUGG)
IAM	International Association for Meteorology (IUGG); previous name for IAMAS
IAMAP	International Association of Meteorology and Atmospheric Physics (IUGG); previous name for IAMAS
IAMAS	International Association of Meteorology and Atmospheric Sciences (IUGG)

IAPO	International Association of Physical Oceanography (IUGG); previous name for IAPSO
IAPSO	International Association for the Physical Sciences of the Oceans (IUGG)
IAPWS	International Association for the Properties of Water and Steam
IASC	International Arctic Science Committee
IASH	International Association of Scientific Hydrology (IUGG); previous name for IAHS
IASPEI	International Association of Seismology and Physics of the Earth's Interior (IUGG)
IASPEI91	seismic travel-time model, without special meaning
IASY	International Years of the Active Sun
IATME	International Association of Terrestrial Magnetism and Electricity (IUGG); previous name for IAGA
IAU	International Astronomical Union
IAV	International Association of Volcanology (IUGG); previous name for IAVCEI
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior (IUGG)
ICACGP	International Commission of Atmospheric Chemistry and Global Pollution (IAMAS)
ICAE	International Commission on Atmospheric Electricity (IAMAS)
ICAO	International Civil Aviation Organization
ICCE	International Commission on Continental Erosion (IAHS)
ICCL	International Commission on Climate (IAMAS)
ICCLAS	International Commission on the Coupled Land-Atmosphere System
ICCP	International Commission of Clouds and Precipitation (IAMAS)
ICCT	Inter-Commission Committee on Theory (IAG)
ICDM	International Commission on Dynamical Meteorology (IAMAS)
ICES	International Council for the Exploration of the Sea
ICET	International Centre for Earth Tides
ICGEM	International Centre for Global Earth Models
ICGW	International Commission on Groundwater (IAHS)
ICMA	International Commission on the Middle Atmosphere (IAMAS)
ICPAE	International Commission on Planetary Atmospheres and their Evolution (IAMAS)
ICPM	International Commission on Polar Meteorology (IAMAS)
ICRCM	International Centre on Recent Crustal Movements
ICRS	International Commission on Remote Sensing (IAHS)
ICSH	International Commission on Statistical Hydrology (IAHS)
ICSI	International Commission on Snow and Ice (IAHS)
ICSIH	International Commission on Snow and Ice Hydrology (IAHS)
ICSU	International Council for Science; formerly, International Council of Scientific Unions
ICSW	International Commission on Surface Water (IAHS)
ICT	International Commission on Tracers
ICTP	Abdus Salam International Centre for Theoretical Physics
ICWQ	International Commission on Water Quality (IAHS)
ICWRS	International Commission on Water Resources Systems (IAHS)
IDEMS	International Digital Elevation Model Service
IDNDR	International Decade for Natural Disaster Reduction
IDS	International DORIS Service
IEEY	International Equatorial Electrojet Year
IERS	International Earth Rotation Service
IGAC	International Global Atmospheric Chemistry Experiment
IGBP	International Geosphere-Biosphere Programme
IGC	International Geological Congress
IGEMS	Integrated Global Earth Monitoring System
IGeS	International Geoid Service
IGETS	International Geodynamics and Earth Tide Service
IGFS	International Gravity Field Service
IGRF	International Geomagnetic Reference Field
IGS	International GNSS Service (previously International GPS Geodynamics Service, International Service for Geodynamics)
IGS	International Glaciological Society

IGSN 71	International Gravity Standardization Net 1971
IGY	International Geophysical Year
IHA	International Hydrology Association
IHD	International Hydrological Decade
IHDP	International Human Dimensions Programme
IHP	International Hydrological Programme
IHY	International Heliophysical Year
IIOE-2	Second International Indian Ocean Expedition
iLEAPS	Integrated Land Ecosystem-Atmosphere Processes Study
ILP	International Lithosphere Program
ILRS	International Laser Ranging Service
ILS	International Latitude Service
IMO	International Meteorological Organization; former name for the WMO
IOC	Intergovernmental Oceanographic Commission
IOC or IO_3C	International Ozone Commission (IAMAS)
IOS	UK Institute of Oceanographic Sciences
ION	International Ocean Network
IPA	International Permafrost Association
IPCC	International Panel on Climate Change
IPGH	Instituto Panamericano de Geografia Historia (also PAIGH)
IPMS	International Polar Motion Service
IPY	International Polar Year
IPYDIS	IPY Data and Information Service
IQSY	International Years of the Quiet Sun
IRC	International Research Council
IRC	International Radiation Commission (IAMAS)
IRDR	Integrated Research on Disaster Risk
ISA	International Seismological Association
ISC	International Science Council
ISC	International Seismological Centre (UK)
ISG	International Service for the Geoid
ISGI	International Service of Geomagnetic Indices
ISO	International Organization for Standardization
ISS	International Seismological Summary
ISSC	International Social Science Council
ITD	inter- and trans-disciplinary
ITRF	International Terrestrial Reference Frame
ITU	International Telecommunications Union
IUBS	International Union of Biological Sciences
IUCI	Inter-Union Commission on the Ionosphere
IUCRM	Inter-Union Commission on Radio Meteorology
IUCSTP	Inter-Union Commission on Solar-Terrestrial Physics
IUGG	International Union of Geodesy and Geophysics
IUGS	International Union of Geological Sciences
IUPAC	International Union of Pure and Applied Chemistry
IUPAP	International Union of Pure and Applied Physics
IVS	International VLBI Service for Geodesy and Astrometry
IY	International Year
IYD	International Year of Deltas
IYGU	International Year of Global Understanding
IYPE	International Year of the Planet Earth
JCS	The Joint Committee on the Properties of Seawater
JPOTS	Joint Panel on Oceanographic Tables and Standards
KIT	Karlsruhe Institute of Technology, Germany

LACSC	Latin American and Caribbean Seismological Commission
LOICZ	Land-Ocean Interactions in the Coastal Zone
MAP	Middle Atmosphere Programme
MEMS	micro-electro-mechanical systems
MOCA-09	Meteorology, Ocean and Cryosphere Assembly, held in Montreal in 2009
MOCA-21	Meteorology, Ocean and Cryosphere Assembly, to be held in Busan, Republic of Korea, in 2021
m.s.l.	mean sea level
NASA	National Aeronautics and Space Administration (USA)
NMSOP-2	New Manual of the Seismological Observatory Practice (second edition)
NNR NUVEL-1A	No Net Rotation Northwestern University Velocity model 1A
NSIDC	National Snow and Ice Data Center (USA)
OGO	Orbiting Geophysical Observatory
OSIL	Ocean Scientific International Ltd.
PAIGH	Pan-American Institute of Geography and History (also IPGH)
PC	personal computer
PIAHS	Proceedings of IAHS
PIOSA	Pan-Indian Ocean Science Association
POGO	Polar Orbiting Geophysical Observatory
PRC	People's Republic of China
PREM	Preliminary Reference Earth Model (IASPEI)
PSA	Pacific Science Association
PSFG	Permanent Service on the Fluctuations of Glaciers
PSMSL	Permanent Service for Mean Sea Level
PSS-78	Practical Salinity Scale 1978
PUB	Prediction in Ungauged Basins program (IAHS)
RETrig	Réseau Européen de Triangulation
REUN	Réseau Européen Unifié de Nivellement
ROC	Republic of China
ROSTSEA	UNESCO Regional Office for Science and Technology for Southwest Asia
SA	scientific assembly
SCAR	Scientific Committee on Antarctic Research
SCL	Scientific Committee on the Lithosphere
SCOPE	Scientific Committee on Problems of the Environment
SCOR	Scientific Committee on Ocean Research
SCOSTEP	Scientific Committee on Solar-Terrestrial Physics
SCOWAR	Scientific Committee on Water Research
SDG	Sustainable Development Goal
SDO	Solar Dynamics Observatory
SEAN	Scientific Event Alert Network
SEDI	Commission on Study of Earth's Deep Interior (IUGG)
SFE	solar flare effect
SHS	Section d'Hydrologie Scientifique (IUGG)
SI	Smithsonian Institute for Natural Sciences
SLR	satellite laser ranging
SnowMIP	Snow Model Intercomparison Project
SOHO	Solar and Heliospheric Observatory
SOLAS	Surface Ocean-Lower Atmosphere Study
SP6	seismic travel-time model, without special meaning
SPARC	Stratosphere-troposphere Processes And their Role in Climate
S_R	Reference Salinity
SSC	storm sudden commencement
SST	Sea surface temperature
SV	Section of Volcanology (IUGG)
TEOS-10	Thermodynamic Equation of Seawater – 2010

TFDC	Task Force for Developing Countries (IAHS)
TGF	transient gamma ray bursts
TLE	transient luminous events
TS/WGI	Technical Secretariat for the World Glacier Inventory
UAV	unmanned aerial vehicles
UCCS	Commission for the Cryospheric Sciences (IUGG)
UCDI	Commission on Data and Information (IUGG)
UCPS	Commission on Planetary Sciences (IUGG)
UGGI	Union Géodésique et Géophysique Internationale (French name of IUGG)
UK	United Kingdom
UMC	Upper Mantle Committee
UMP	Upper Mantle Project
UN	United Nations
UNEP	UN Environmental Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNISDR	United Nations Office for Disaster Risk Reduction, established to ensure the implementation of the International Strategy for Disaster Reduction
URSI	Union Radio Scientifique Internationale (International Union of Radio Sciences)
USA	United States of America
USD	USA dollar
USSR	Union of Soviet Socialist Republics
UV radiation	ultraviolet radiation from the Sun
VERSIM	VLF/ELF Remote Sensing of Ionospheres and Magnetospheres
VLBI	very long baseline interferometry
WCRP	World Climate Research Programme
WDMAM	World Digital Magnetic Anomaly Map
WDC	World Data Center
WDS	World Data System
WG	working group
WGH	Union Working Group on History of Earth and Space Sciences (IUGG)
WGMS	World Glacier Monitoring Service
WMO	World Meteorological Organization
WMS	World Magnetic Survey
WWI	First World War
WWII	Second World War

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Open Access History of Geo- and Space Sciences

IUGG: beginning, establishment, and early development (1919–1939)

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Abstract. The International Union of Geodesy and Geophysics (IUGG) was established in 1919 to promote activities of already-existing international scientific societies dealing with geodesy, terrestrial magnetism and electricity, meteorology, physical oceanography, seismology, and volcanology. At the first General Assembly a Section of scientific hydrology was added, making a total of seven Sections of the Union. This paper introduces IUGG by presenting its current mission, structure, partners, and programs; discussing various international geophysical efforts before its origin; and describing the Union's development from the end of World War I to the beginning of World War II. During this period (1919–1939), the number of member countries increased from the 9 founding Member countries to 35; seven General Assemblies were held, each in a different international venue; and the number of delegates attending the assemblies increased from a few dozen to more than 800 scientists. At the Fifth General Assembly in 1933, the term "section" was replaced by "international association". Each General Assembly of the Union, since the First General Assembly in Rome, Italy, in 1922 to the VII General Assembly in Washington, DC, USA, in 1939, is summarized, and the distinguished scientists who contributed to the Union's formation and it early development are introduced.

1 Introduction

The International Union of Geodesy and Geophysics (IUGG; http://www.iugg.org, last access: 20 February 2019) celebrates its 100th anniversary in 2019. Under its umbrella, eight international scientific associations and several interdisciplinary bodies comprising about 100 divisions, commissions, committees, working groups, and geodetic and geophysical services cover almost all disciplines of geo- and space sciences and promote research of the Earth from its core to its space environment up to the Sun. It is dedicated to advancing basic (fundamental) science and to solving challenging societal problems such as climatic and environmental changes, disaster risk reduction, water security and quality, and energy.

Written for the occasion of IUGG's centennial, this and two subsequent articles in this special issue document the history, current activities, and possible future development of IUGG. To appreciate the history of IUGG, we start the paper with a description of the Union and its current structure, partnerships, and operating principles. Then we look back to examine the founding and early history of the Union from the end of the First World War (WWI) and the beginning of the Second World War (WWII), including descriptions of early General Assemblies and distinguished leaders. Two other papers cover (i) the Union's history after WWII until the end of the last century and (ii) its development in the 21st century. These papers do not pretend to offer a comprehensive and definitive account of all activities of the Union for the last 100 years, but rather highlight major activities of and administrative and structural changes in IUGG during that time.

2 IUGG today

IUGG is a dynamic non-governmental, not-for-profit, scientific organization that brings together scientists and science organizations from many countries in which geophysical sciences and geodesy have a role. IUGG encompasses multiple scientific disciplines through its associations and commissions, and hundreds of thousands of individuals from all over the world through its Adhering Organizations (e.g., national academies, research councils, governmental agencies). IUGG has a long and storied history; about 100 countries have been IUGG members for a full century, and since its founding in 1919, the Union has had two official languages: English and French. The official title of the Union in French is l'Union Géodésique et Géophysique Internationale (UGGI).

IUGG is governed by a Council of its Adhering Bodies, and cooperates with an impressive list of international and intergovernmental organizations. Any country that has developed independent activity in geodesy and geophysics may adhere to the Union. National Members (the Adhering Body) set up IUGG National Committees that organize IUGG-related activities in their countries. Many scientists participate in Union activities through these National Committees and represent their countries at IUGG general assemblies.

Presently, there are four categories of membership: Regular (the Adhering body has paid annual dues set by the Finance Committee); Observer (payment of dues has temporarily lapsed); Associate (the Adhering Body otherwise meets the criteria for regular membership but does not pay dues); and Affiliate (organizations awarded the same rights, duties and obligations as Associate Members). Membership waxes and wanes for reasons including changes in financial circumstances, politics, and scientific activity. For instance, financial problems experienced by a scientific institution adhering to the union may lead to the loss of membership for the country involved. Many political borders have changed since 1919, which at times affects member countries. Less-affluent countries may lack a critical mass of scientists to share the mission and major purposes of international unions, or severe political, economic, and financial problems may prevent regular membership (Ismail-Zadeh, 2016a). Scientists in these countries are encouraged to participate in IUGG's scientific activities for the benefit of science in their countries and for their contribution to geographic coverage that is crucial for global geoscience.

Between face-to-face meetings of the Council that take place at quadrennial General Assemblies of the Union, the affairs of the Union are vested in the Bureau and the Executive Committee (Fig. 1). The Bureau consists of the President, President-Elect, Secretary General, Treasurer, and three additional Members, elected by the Council. The Executive Committee consists of the Bureau, the Presidents of the International Associations, and the immediate Past President of the Union. The Executive Committee coordinates the scientific work of the Associations and formulates the general policies that guide the scientific objectives of the Union. At each General Assembly, a Finance Committee of three members is elected also by the Council. Besides advising the Council, Bureau, and the Executive Committee on financial matters, the Finance Committee receives and reviews audits of the accounts, advises the Treasurer on preparing the budget and on raising funds to support Union and Association activities, and reviews the category of membership of National Members. Also at each General Assembly, the Council adopts resolutions, i.e., statements affirming a scientific finding or plan of action. These findings are generally recommended to the Council Members by the Associations, which must first adopt the matter at their Association Scientific Assemblies. These resolutions are powerful endorsements of scientific viewpoints that have been used to establish standard nomenclature and methods of measurement, support international scientific campaigns, align global scientific opinion, and obtain funding from governmental and non-governmental agencies. From time to time, between General Assemblies, the IUGG Bureau may issue statements expressing a unanimous opinion on a topic of scientific significance. The most recent statement, issued on 12 June 2017, was entitled "The Earth's climate and responsibilities of scientists and their governments to promote sustainable development".

2.1 Union structure

IUGG is dedicated to advancing, promoting, and communicating knowledge of the Earth system, its space environment, and the dynamical processes causing change. IUGG is a confederation of eight semi-autonomous international scientific associations, each having its own executives, and is responsible for a specific domain of topics or themes within the overall scope of Union activities. These associations are the following.

- International Association of Cryospheric Sciences (IACS)
- International Association of Geodesy (IAG)
- International Association of Geomagnetism and Aeronomy (IAGA)
- International Association of Hydrological Sciences (IAHS)
- International Association of Meteorology and Atmospheric Sciences (IAMAS)
- International Association for the Physical Sciences of the Oceans (IAPSO)
- International Association of Seismology and Physics of the Earth's Interior (IASPEI)

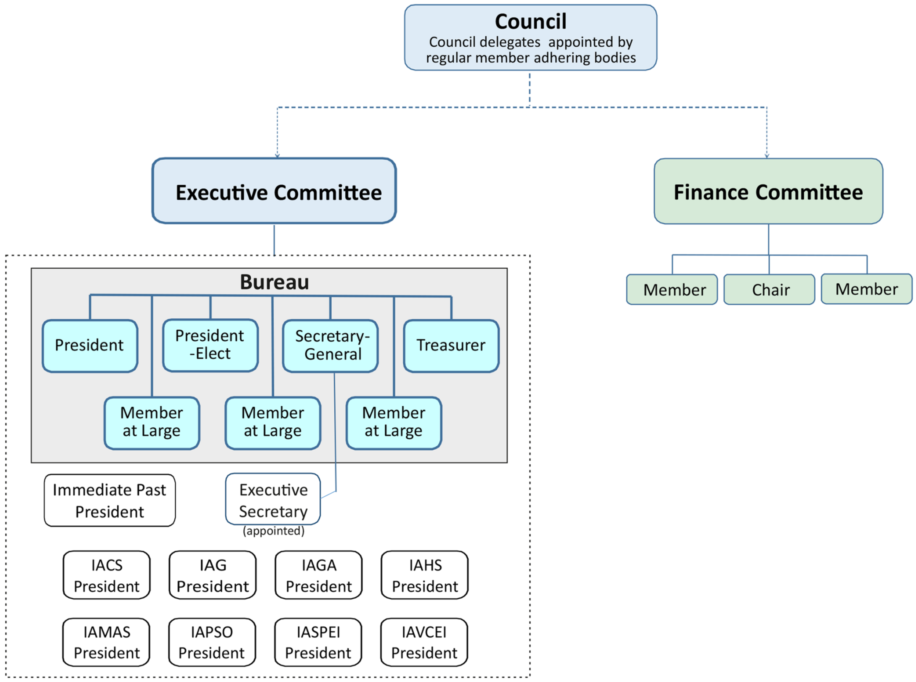

Figure 1. The IUGG governance (designed by F. Kuglitsch).

- International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI)

Within the framework of the Union's Statutes and By-laws, its International Associations adopt their own Statutes and By-laws and control their administration and finance. The beginning, establishment, and historical development of the Union Associations are subjects of related papers in this special issue.

The majority of the Union's scientific work takes place within the Associations and their inter-Association bodies. At present, IUGG and its Associations operate through more than one hundred scientific divisions, commissions, committees, working groups (WGs), and services (see Fig. 1 in Ismail-Zadeh, 2016a). The Union enables interdisciplinary science on topics of common interest through three types of IUGG interdisciplinary bodies: Union commissions, Inter-Association commissions, and Union committees. Union commissions are co-sponsored by at least four associations (listed below) and often share activities with other notable international scientific organizations. IUGG Inter-Association commissions are co-sponsored by two or three associations, the most prominent being the IUGG Tsunami Commission and the IUGG Working Group on Electromagnetic Studies of Earthquakes and Volcanoes (EMSEV). Union and Inter-Association Commissions deal with science, whereas Union committees deal with administration (the names were clarified in 2004). In addition, several ad hoc committees are set up before IUGG General Assemblies to deal with topics such as nominations, site evaluations, and resolutions. At present, the following Union Commissions, Working Group, and Standing Committees are active: Union Commissions on Climatic and Environmental Changes (CCEC), Mathematical Geophysics (CMG), Geophysical Risk and Sustainability (GRC), Study of the Earth's Deep Interior (SEDI), Data and Information (UCDI), and Planetary Sciences (UCPS); the Working Group on History of Earth and Space Sciences; and Standing Committees on Capacity Building and Education, Honors and Recognition, Outreach, Statutes and By-Laws, and Visioning. Brief summaries of the current Union commissions and committees can be found in Appendix A.

2.2 Union programs and products

IUGG has initiated and/or vigorously supported collaborative efforts that have led to highly productive international multi- and interdisciplinary programs. Current IUGG programs include the International Lithosphere Program (ILP), Global Geodetic Observing System (GGOS), Geoscience Education, Publication, Grants, and Honor and Recognition programs. Description of the programs can be found in Appendix B.

IUGG Associations work to set global standards for research and agree on definitions, equations, and algorithms. The Union's products include the International Classification for Seasonal Snow on the Ground, the International Terrestrial Reference Frame, the International Geomagnetic Reference Field, the International Thermodynamic Equation of Seawater, the Manual of Seismological Observatory Practice, and the Guidelines for Professional Interaction During

Volcanic Crises. Detailed description of the products is presented by Ismail-Zadeh (2016a). The internationally driven services and products of IUGG Associations are absolutely unique; they could not be done by any governmental organization even though operations of the services depend on national funding.

2.3 The International Science Council and IUGG

In 1899, representatives of European and US academies met in Wiesbaden, Germany, and established the International Association of Academies, which was active until WWI (Greenaway, 1996). Already during WWI, scientific leaders from the allied nations thought about the post-war renewal of international scientific cooperation because of political and scientific reasons (Good, 2000). Representatives of national academies of allied countries met in London, Great Britain, in October 1918 and then in Paris, France, in November 1918, and decided to establish an International Research Council (IRC; Wood, 1919). The IRC was established in Brussels, Belgium, in July 1919, together with several scientific unions including IUGG. The main aims of the Council were "(i) to coordinate international efforts in the different branches of science and its applications; (ii) to initiate the formation of international associations or unions deemed to be useful to the progress of science; (iii) to direct international scientific action in subjects which do not fall within the province of any existing association; and (iv) to enter, through the proper channels, into relations with the Governments of the countries adhering to the Council to recommend the study or questions falling within the competence of the Council" (Lyons, 1919). At the beginning, IRC was a non-inclusive council by its laws excluding the Central Powers from membership in the Council and its scientific unions, and admitting neutral countries only by a three-quarters majority vote. However, that, immediately after the end of WWI, about two hundred members of the academies of neutral nations called on the members of the academies of allied nations "for cooperation in order to prevent science from becoming divided, for the first time and for an indefinite period, into hostile political camps" (Scientific Events, 1919). The Council was a part of the general post-WWI policy of isolating the Central Powers (Cock, 1983). Only in 1926, IRC agreed to delete from its Statutes the clause related to exclusion of the Central Powers from membership, and invited Austria, Bulgaria, Germany, and Hungary to adhere to IRC. Unfortunately, none of these countries could join IRC at that time for a variety of reasons (IRC, 1928; Greenaway, 1996).

The IRC was active until 1931, when the International Council of Scientific Unions (ICSU) was established to promote international scientific activity in different branches of science and interdisciplinary research between the unions. IUGG was one of the active supporters behind establishing ICSU and became a founding member of the Council. ICSU formally changed its name to the International Council for Science at an Extraordinary Assembly in 1998, keeping its acronym and logo to maintain historical continuity. ICSU provided a global forum for scientists in all scientific disciplines to exchange ideas and information and to develop standard methods and procedures for all fields of research. IUGG brought expertise on Earth and environmental studies from researchers in its International Associations and Union commissions. IUGG strongly supported ICSU's policy of non-discrimination, which affirms the rights and freedom of scientists throughout the world to engage in international scientific activity without limitation by such factors as citizenship, religion, creed, political stance, ethnic origin, race, color, language, age or gender.

At the ICSU extraordinary General Assembly and the General Assembly of the International Social Science Council (ISSC) held in Oslo, Norway, in October 2016, ICSU and ISSC members agreed to merge the two councils. In October 2017, a new organization, International Science Council (ISC), was founded at the joint ICSU and ISSC General Assembly in Taipei to advance science as a global public good and to act as a global voice of science, and was formally established on 30 June 2018. Although initially IUGG and some other ICSU and ISSC Members questioned the necessity and urgency of the merger (24 % of the ICSU Members and 13 % of the ISSC Members voted against it), IUGG was convinced later that the merger would benefit scientific development and play significant role in bridging science to society and policymaking. IUGG became a founding member of the new Council. The inaugural General Assembly of ISC was held on 3–5 July 2018 in Paris, France, where the first Governing Board of the new Council was elected. IUGG Secretary General Alik Ismail-Zadeh was elected the first Secretary of Council.

IUGG had participated in ICSU's leadership since its inception in 1931. The first Secretary General of the Council was Sir Henry George Lyons, IUGG Secretary General (1919–1930) and the IRC Secretary General (1928–1931) (Cheetham, 1947). In recent years, Vladimir Keilis-Borok (IUGG President, 1987–1991), Uri Shamir (IUGG President, 2003–2007), and Guoxiong Wu (IUGG Executive Committee Member and IAMAS President, 2007–2011) have served on the ICSU Executive Board. Tom Beer (IUGG President, 2007–2011) and Harsh Gupta (IUGG President, 2011–2015) have served on the ICSU Committee on Science Planning and Review. Gordon McBean (Member of the IUGG Bureau, 1987–1995) served as the last ICSU President from 2014 until 2018, when the new council was formed.

IUGG cooperates with ISC International Scientific Unions, especially those dealing with Earth and space sciences, to promote the interdisciplinary sciences worldwide (see about GeoUnions in Joselyn et al., 2019). There are a number of ISC scientific committees for which IUGG appoints liaisons to foster cooperation between the interdisciplinary committees and IUGG. These include the Committee on Data for Science and Technology (CODATA); the Committee on Space Research (COSPAR); the Scientific Committee on Antarctic Research (SCAR); the Scientific Committee on Oceanic Research (SCOR); the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP); the World Data System (WDS); and the ISC Regional Offices for Africa, Asia and the Pacific, and Latin America and the Caribbean. IUGG is particularly active with the Scientific Programme of Integrated Research on Disaster Risk (IRDR) co-sponsored by ISC and the United Nations Office for Disaster Risk Reduction (UNISDR), and the World Climate Research Programme (WCRP) co-sponsored by ICSU, the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC) of the UN Educational, Scientific and Cultural Organization (UNESCO).

ICSU provided grants to promote major scientific campaigns proposed by the participating Unions, and IUGG proposals have often been successful. For example, in 2010, IUGG received an ICSU grant for a project proposal, "Extreme Natural Hazards and Societal Implications – ENHANS"; in 2011, for a project proposal, "eGYAfrica – better Internet connectivity for research and education institutions in Africa"; and in 2014, for a project proposal, "Uniting and networking the magnetic community in the northern Indian Ocean region".

2.4 Partners

IUGG envisions a future Earth that is environmentally sustainable and where societies are resilient against natural hazards. To achieve this goal, participation in global networks of interdisciplinary programs is vital. IUGG places particular emphasis on the scientific problems of economically less-developed countries by sponsoring activities relevant to their scientific needs. In addition to the many beneficial relationships that IUGG Associations develop with partners, IUGG as a whole also develops and maintains formal contacts with a wide range of organizations, detailed here (see Fig. 2 for the partners of the Union).

The formation of the United Nations (UN) in 1945 and its specialized agencies broadened the scope of international involvement of IUGG in scientific programs (Ismail-Zadeh, 2016a). Through its Associations, IUGG has established productive relationships with WMO; UNESCO; the UN Cartographic Section (now the UN Geospatial Information Section); the International Civil Aviation Organization (ICAO); the UN Committee of Experts on Global Geospatial Information Management (UN-GGIM); and the UN Environmental Program (UNEP). Cooperation with WMO includes meteorology (via IAMAS), hydrology (IAHS), cryosphere (IACS), space weather (IAGA), and volcanology (IAVCEI), and extends to its specialized bodies such as the Global Framework for Climate Sciences (GFCS). Particularly, after the 2010 Eyjafjallajökull volcano eruption and at ICAO's request, WMO and IUGG established a joint Volcanic Ash Scientific Advisory Group (VASAG) to provide scientific advice on volcanic ash to civil aviation. Representatives of IUGG have been invited to WMO Executive Congresses and representatives of WMO have been invited to IUGG General Assemblies.

IUGG had established in 1946 (Stagg, 1947) and maintains a working relationship with UNESCO and its scientific bodies, including IOC and International Hydrological Programme (IHP) through IAPSO and IAHS since those bodies' establishment in 1960 and in 1975, respectively. For example, IAHS established the International Hydrology Prize in 1981 in cooperation with IHP and WMO to award distinguished scientists who have made an outstanding contribution to hydrological science. For years, IUGG via IASPEI and IAVCEI cooperated with the UNESCO section on Earth Science and Geohazard Risk Reduction in the framework of its programs related to earthquake and volcano hazards and risks, and since 2017, in the framework of the International Geoscience and Geoparks Programme. IUGG also cooperates with the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) Preparatory Commission in studies related to seismology, hydroacoustics, and atmospheric transport modeling and assists scientifically in organizing the CTBT Science & Technology conferences. Compared to intergovernmental organizations, which are constrained by their governmental framework, IUGG and other non-governmental, international scientific unions, provide independent advice on scientific subjects within their expertise.

The UN General Assembly adopted the 2030 Agenda for Sustainable Development in 2015 (https://sustainabledevelopment.un.org/sdgs, last access: 20 February 2019). The Agenda seeks to link issues such as climate change, natural disasters and education. It intertwines social, economic, and environmental targets in 17 Sustainable Development Goals (SDG). Each of the SDGs is divided into several sub-goals. All IUGG Associations, the Union Commissions on Geophysical Risk and Sustainability, Climatic and Environmental Change, and Data and Information as well as the IUGG Committee on Capacity Building and Education seek to contribute to the sub-goals related to climatic change, natural hazards and risk, gender issues, education and capacity building, research and innovation (Ismail-Zadeh, 2016b).

The Group on Earth Observations (GEO) is a voluntary partnership of governments and international organizations that provides a framework for developing projects and coordinating strategies and investments among partners. GEO coordinates efforts to build a Global Earth Observation System of Systems (GEOSS). At the GEO-X Plenary in 2014, IUGG was unanimously recognized as a Participating Organization of GEO, although several of IUGG's bodies, including IAG, had earlier been Participating Organizations.

Through IAG, IUGG also names liaisons to and partners with the Consultative Committee for Time and Frequency (CCTF) and the Pan American Institute of Geography and History (PAIGH). The CCTF is a body of the Bureau International des Poids et Mesures (BIPM), the inter-governmental

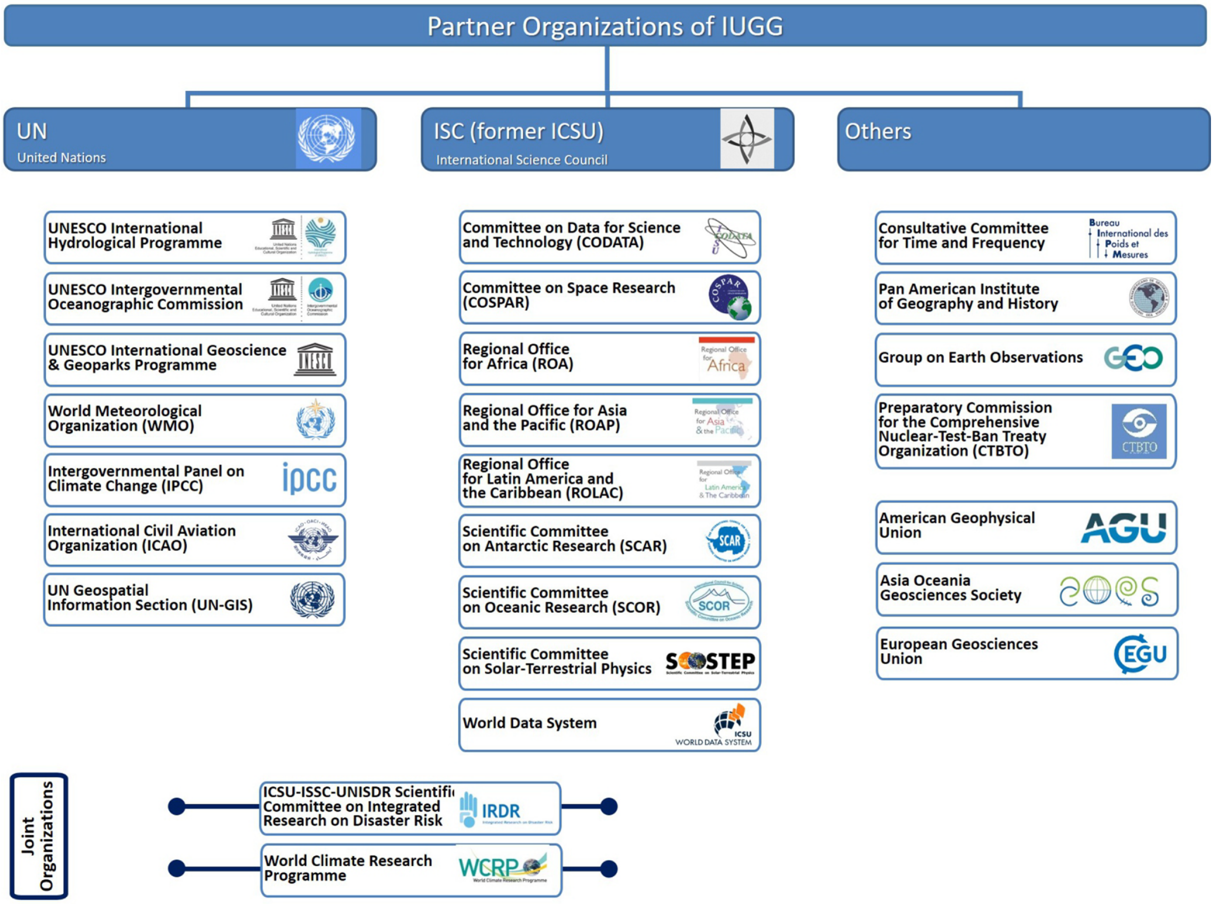

Figure 2. Scientific partner organizations (designed by F. Kuglitsch).

organization through which member states act together on matters related to measurement science and standards such as the leap second. PAIGH is a technical and scientific body of the Organization of American States.

3 Early development of IUGG

It is difficult to trace back to the earliest date when international cooperation in geodesy and geophysics began, but it is evident that such cooperation became important in the early 19th century. For example, in the first decades of the 19th century, Edward Sabine, an Irish astronomer and geophysicist, and Alexander von Humboldt, a German geographer and naturalist, together with a few other scientists, organized widespread magnetic observations (Good, 2000; Collier, 2014). This motivated Carl Friedrich Gauss, a German mathematician, together with von Humboldt and Wilhelm E. Weber, a German physicist, to found in 1836 the Göttingen Magnetic Union, the first worldwide network of magnetic observatories. This international organization promoted a cooperative scheme of simultaneous observations in which more than 50 observatories distributed over five continents took part (Chapman, 1955; Linthe, 2007). In the 1860s, Johann Jacob Baeyer, a Prussian general and geodesist, was proactive in building scientific cooperation in Europe on measurements of the size and shape of the Earth. He was a driving force in the formation of the Mitteleuropäische Gradmessung (Central European Geodetic Association) in 1862, which became the Association Géodésique Internationale (the International Association of Geodesy, IAG) in 1886 (Angus-Leppan, 1984). Conferences and international contacts were sporadic prior to the second part of the 19th century. Prince Albert I of Monaco, who devoted time and resources to oceanography, granted his patronage to the establishment of the International Marine Association in 1900 (Smythe-Wright et al., 2019). John Milne, a British geologist and mining engineer who was invited by the Japanese government to Tokyo in 1875, established the Seismological Society of Japan together with British and Japanese physicists and seismologists. The First International Conference on Seismology was held in Strasbourg (then a German city) in 1901, and the International Seismological Association was founded in 1904 (Pomerantzef, 1904; Schweitzer, 2003).

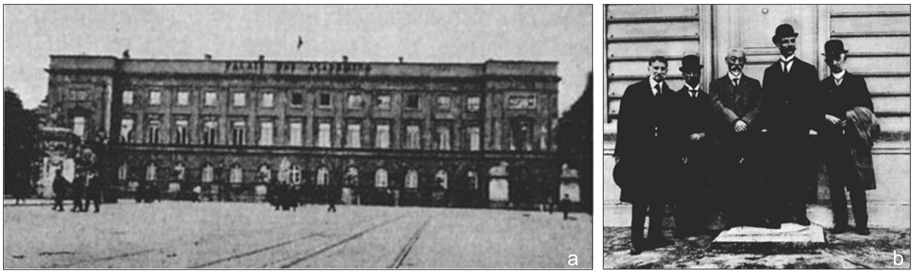

Figure 3. The inaugural IRC General Assembly and establishment of IUGG. **(a)** Palais des Academies at Brussels, Belgium, where the IRC assembly was held in July 1919; **(b)** IUGG officers: (from left to right) Louis A. Bauer, V. Reina, Aikitsu Tanakadate, Hermant, and Charles Chree participating in the Assembly (Bauer, 1919).

By the outbreak of WWI in 1914, international organizations for geodesy, seismology, meteorology, geomagnetism, geoelectricity, and oceanography had already been established. The war interrupted the operation of these bodies, although some were kept active by then-neutral nations. During WWI, some scientific leaders from the allied nations gave thought to the post-war renewal of international scientific cooperation. Though early efforts in international cooperation within international associations and the network of national academies were very successful, discussion between existing geoscientific societies and national academies was limited, forcing scientists to devise a new model of cooperation (Good, 2000; Ismail-Zadeh, 2016a). In 1918, representatives of the scientific academies of allied nations decided to foster international scientific cooperation, and establish together with the IRC scientific unions to organize and promote international cooperation. In particular, a resolution was passed in favor of establishing an international geophysical union "for the purpose of initiating and promoting researches in geophysics" (Wood, 1919), to be made up of all existing scientific groupings dealing with the physical sciences of the Earth. The original proposal for the name of the union was the "international geophysical union" (Ismail-Zadeh, 2016a). However, in May 1919, at a preliminary meeting, the IRC adopted an expanded name, "International Union of Geodesy and Geophysics" (IUGG), based on a motion of the representative from Italy (Bauer, 1919). The motivation of the Italian representative is unknown; one conjecture is that in the beginning of the 20th century geodesy positioned itself as a branch of mathematics rather than a branch of physical sciences, and this may be the reason why geodesy was listed separately from all other physical disciplines of IUGG at the time of the Union's establishment (Ismail-Zadeh, 2016a). At the same meeting, draft Statutes for IUGG were adopted. The International Astronomical Union (IAU) was formed at the same time; one reason for the early establishment of these two unions was that in both cases "their basic studies had always required international action so international 'union' came naturally" (Greenaway, 1996).

The formation of IUGG was finalized at the first IRC General Assembly held on 18–28 July 1919 (Fig. 3), with the approval of its Statutes and future activities (Lyons, 1919). The first nine Member countries of IUGG were Australia, Belgium, Canada, France, Italy, Japan, Portugal, the United Kingdom, and the United States of America. IUGG included several branches of science for which special organizations had existed for many years, well before WWI. They were reconstituted as six Sections within IUGG, each with its own executive committee. According to Bauer (1919), those initial Sections were (1) Geodesy (President William Bowie, USA, and Secretary Georges Perrier, France); (2) Terrestrial Magnetism and Electricity (President Aikitsu Tanakadate, Japan, and Secretary Louis Agricola Bauer, USA); (3) Meteorology (President Sir William Napier Shaw, UK, and Secretary Charles Frederick Marvin, USA); (4) Physical Oceanography (naming of a President was deferred, and Secretary Giovanni P. Magrini, Italy; later Prince Albert I of Monaco was elected President of this Section); (5) Seismology (the organization of the Section was deferred because of the agreement among the founding member countries regarding the continuation of the International Seismological Association); and (6) Volcanology (President Annibale Riccò, Italy, and Secretary Alessandro Malladra, Italy). Charles Lallemand (France) became the first President of the Union, serving until 1933, and Sir Henry G. Lyons was the first IUGG Secretary General, serving until 1930. Four Vice-Presidents were named: H. S. H. Prince Albert I of Monaco, Bowie (USA), Sir Shaw (UK), and Tanakadate (Japan).

Although German scientists and academies played an important role in the establishment of international associations in geodesy and seismology, the involvement of Germany and other countries of the Central Powers as well as Russia in geodetic and geophysical cooperation was interrupted by WWI and the Russian Revolution in 1917. Following the IRC rules, the IUGG membership at the beginning was restricted to the allied and neutral nations. Although the ISC restriction on the membership was removed in 1926, and IUGG's own membership became more inclusive, the international cooperation between allied, Central Power, and neutral countries resumed to the full extent only after WWII (Cock, 1983; Good, 2000; Ismail-Zadeh, 2016a).

The Union was established for the period of 12 years, subject to renewal and modification at the end of this period. Delegates of IUGG Member countries agreed to hold general assemblies of the Union every 3 years. Also, they decided that the Union could meet at any place and not necessarily at the same place as the IRC, and Union Sections could call special meetings when they found them necessary. The objectives of the Union as stated in the Statutes were (1) to promote the study of problems concerned with the figure and physics of the Earth; (2) to initiate and coordinate researches which depend upon international cooperation and to provide for their scientific discussion and publication; and (3) to facilitate special researches such as the comparison of instruments used in different countries (Bauer, 1919).

4 IUGG General Assemblies

IUGG has held general assemblies (GAs) since 1922 (quadrennially since 1963). Its first assemblies gathered only a few hundred scientists, and the GA in Washington, DC, USA, in 1939 was attended by more than 800 people, although only a little more than 200 foreign scientists could participate due to the war. Table 1 presents some statistics related to the Union's first seven GAs, and Table 2 lists Member countries connected with the Union from 1919 to 1939.

4.1 First General Assembly (3–10 May 1922, Rome, Italy)

The First General Assembly (GA) brought together delegates from the founding Member countries and from four new Member countries (Brazil, Greece, Mexico, and Spain), and a number of representatives from other countries that had not yet joined the Union. The sessions were held in the Reale Accademia dei Lincei. The delegates were welcomed by the Minister of Public Instruction at the Capitol in the presence of His Majesty the King of Italy (Lyons, 1922). All Sections had made good progress in planning international cooperation in the years since 1919, and work plans were adopted for the next 3 years. In 1919 at the GA in Brussels, it was suggested that the study of variation of latitude should be confided to the IAU. At the GA in Rome this question was discussed in detail with the IAU representatives; it was decided that the subject should remain with the Section of Geodesy, and a joint committee of geodesists and astronomers was appointed to direct the work. As the International Association of Seismology still existed at the time of the GA in Brussels, the IUGG Section of Seismology was only formally constituted at Rome. Seismologists discussed topics related to microseisms, earthquake focal depths, and wave propagations (Lyons, 1922). One of the important discussions among meteorologists at the GA was related to the cooperation with the International Meteorological Organization (IMO, the predecessor of the WMO), which brought together meteorological services of several countries. It was agreed that the investigations, which required international cooperation, could be difficult for the national services to include in their activities, and hence the Section of Meteorology could initiate and promote such investigations. The Section of Terrestrial Magnetism and Electricity discussed the methods of observation required for different types of instruments, and the possibilities for international comparison of instruments. The Section of Physical Oceanography discussed how to facilitate international cooperation in physical oceanography, and how the collection of tidal information could be improved. The Section of Volcanology discussed the classification of volcanic phenomena, and studies of the thermal gradients in several regions. At that GA, a Section of Scientific Hydrology was added, making a total of seven Sections. Also at that GA, it was decided that instead of electing Vice-Presidents, the Presidents of the IUGG Sections would serve in that capacity. Charles Lallemand (France) was elected IUGG President, and Sir Henry G. Lyons (UK) Secretary General.

4.2 Second General Assembly (1–8 October 1924, Madrid, Spain)

The Second General Assembly of IUGG was held in Madrid at the invitation of the Spanish Government. Ten new Member countries adhered to the Union by 1924 (Table 2). The scientific work of the GA was carried on in the seven Union Sections. In the Section of Geodesy, an International Ellipsoid of Reference (a surface that approximates the geoid, that is, the Earth's figure) was discussed and adopted. In the Section of Seismology, it was decided to continue the publication of the International Seismological Summary at Oxford. A joint meeting of the Sections of Meteorology and Physical Oceanography on marine meteorology, and a joint meeting of the Sections of Meteorology and Scientific Hydrology on the measurement of rainfall data were organized. The Section of Terrestrial Magnetism and Electricity decided to promote studies on the international comparison of instruments, and on the magnetic and electrical characterization of days. Much attention was given to echo-sounding and to tidal phenomena by the Section of Physical Oceanography, which also discussed jointly with the Section of Geodesy the subject of earth tides. Changes in the geothermal gradient in the vicinity of volcanoes were discussed at a joint meeting of the Sections of Volcanology and Seismology. Valuable reports on the 1923 Great Kanto earthquake in Japan and on the gauging of the Nile discharge were presented at the GA. The extension of the work by the Section of Scientific Hydrology to the phenomena of glaciers was also considered. The Spanish Government hosted the GA in the Chamber of Deputies, and His Majesty the King of Spain presided at the Opening Ceremony of the GA; a reception was held at the Palace by their Majesties the King and the Queen, to which all the delegates were invited (Lyons, 1924).

Table 1. IUGG General Assemblies from 1922 to 1939, and IUGG Presidents and Secretaries General.

No. GA	Year	Place	No. attendees	No. Member countries	President	Secretary General
1	1922	Rome, Italy	–	13	Charles Lallemand	Sir Henry George Lyons
2	1924	Madrid, Spain	∼ 150	24	(France, 1919–1933)	(UK, 1919–1930)
3	1927	Prague, Czechoslovakia	∼ 160	30		
4	1930	Stockholm, Sweden	331	33		
5	1933	Lisbon, Portugal	200	34	William Bowie	Harold St. John Lloyd Winterbotham
					(UK, 1930–1946)	(USA, 1933–1936)
6	1936	Edinburgh, UK	344	34	Dan Barfod La Cour	
7	1939	Washington DC, USA	805	35	(Denmark, 1936–1942)	

Table 2. IUGG Member countries (1919–1939).

No.	Members	Date of admission	No.	Members	Date of admission
1	Australia	1919	19	Chile	1924
2	Belgium	1919	20	Egypt	1924
3	Canada	1919	21	Morocco	1924
4	France	1919	22	Poland	1924
5	Italy	1919	23	South Africa	1924
6	Japan	1919	24	Uruguay	1924
7	Portugal	1919	25	The Netherlands	1925
8	UK	1919	26	Peru	1925
9	USA	1919	27	Argentina	1927
10	Brazil	1922	28	Finland	1927
11	Greece	1922	29	New Zealand	1927
12	Mexico	1922	30	Tunisia	1927
13	Spain	1922	31	Bulgaria	1930
14	Denmark	1923	32	Hungary	1930
15	Norway	1923	33	Romania	1930
16	Sweden	1923	34	Vietnam	1931
17	Switzerland	1923	35	Colombia	1938
18	Thailand	1923			

4.3 Third General Assembly (3–10 September 1927, Prague, Czechoslovakia)

The Third General Assembly was held in Prague at the invitation of the Czechoslovakian Government (Fig. 4). Six new Member countries adhered to IUGG by 1927 (Table 2). The GA urged the countries concerned to improve the network of existing seismic stations by establishing new stations. A proposal of the US National Committee on international cooperation in the studies of ocean deeps was strongly supported. The Section of Meteorology worked closely with IMO, complementing the work of the other (Davies, 1990); IMO occupied with matters related to the working of the meteorological services in various countries and the Section dealt with many scientific matters related to meteorology and atmospheric physics. The Section of Terrestrial Magnetism and Electricity considered among other topics the works on atmospheric ionization and the observations of auroras, and expressed the need for additional earth current installations. The Section of Physical Oceanography considered the investigations of the different great sea areas and of tidal phenomena. The Section of Volcanology adopted a resolution that countries in which active volcanoes occur should be invited to undertake the measurement of the thermal gradient. The Section of Scientific Hydrology discussed the problems related to the flow of water and the transport of silt in suspension. Also, by agreement with the International Committee on Glaciers (established in 1894), its work was transferred to the Section to be carried out by a committee set up for this aim. Generous hospitality was shown to the GA's delegates by the Czechoslovakian Government and by the municipality of the city of Prague. The President of the Republic was to have received the delegates on one evening, but unfortunately, his health did not allow him to return to Prague, and the Minister of Foreign Affairs hosted the reception on his behalf (Lyons, 1927).

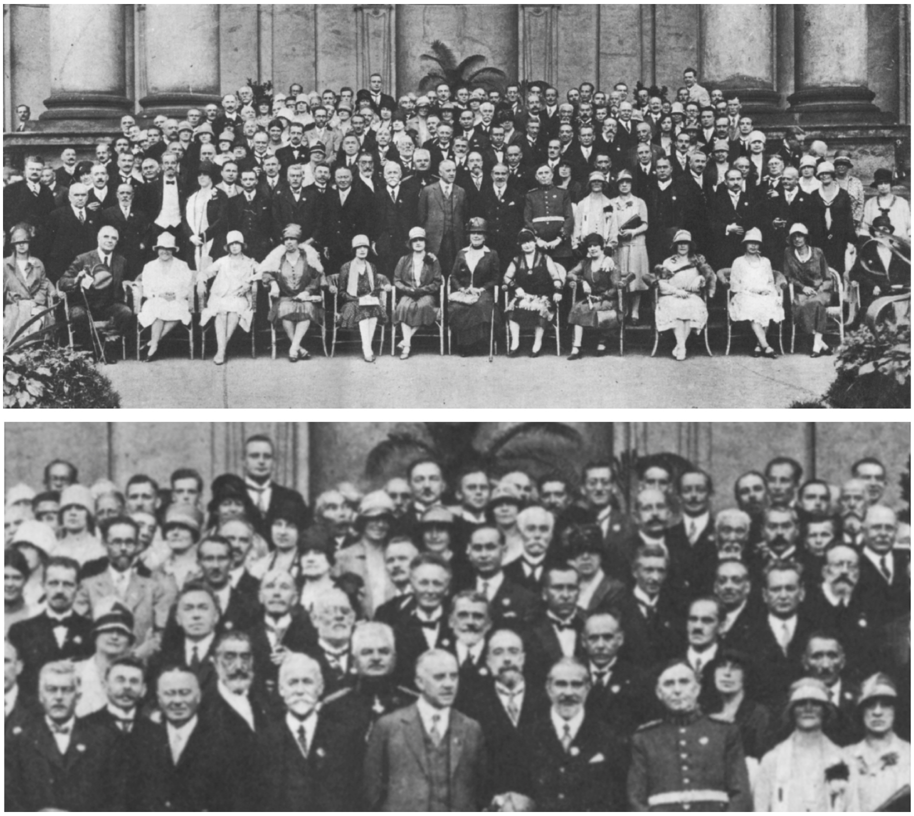

Figure 4. Participants of the Third General Assembly (upper panel); details of the central part of the photo (lower panel) (source: IUGG archives).

4.4 Fourth General Assembly (15–23 August 1930, Stockholm, Sweden)

The Opening Ceremony of the Fourth General Assembly was held in the Concert Hall, where the Chancellor of the Universities and Chairman of the Swedish National Committee welcomed the delegates, and IUGG President Charles Lallemand replied and expressed thanks for hospitality and excellent arrangement of the meeting. Bulgaria, Hungary, and Romania joined IUGG in 1930. The scientific and business meetings of the GA were held in the Parliament House (Fig. 5). Scientific topics were discussed by the Union Sections. Felix A. Vening-Meinesz presented work on the determinations of gravity at sea, and the GA expressed the hope that other nations with submarines could cooperate in the work of gravity determination over ocean areas (Lyons, 1930). Some time was dedicated by several Union Sections to discussing activities during the Second International Polar Year (IPY; 1932–1933); for example, it was decided to publish an auroral atlas as soon as the material could be selected and brought together (Lyons, 1930). Among business topics, the GA discussed changes in the Union's Statutes regarding the admission of new members. The changes were associated with much freedom, which IRC provided to its Union Members in arranging their own affairs based on a new type of relationship – a "cooperative independence" within the IRC family (Spencer-Jones, 1960). Also, the GA agreed to provide greater freedom for the Union's Sections to arrange their activities. The GA decided that future IUGG Presidents would hold office for one term and should not be immediately eligible for re-election, which would assist in maintaining the organization's international character. Swedish hospitality provided a number of occasions at which the delegates could discuss matters of common interest. The City Council gave a banquet in the City Hall, and H. R. H. the Crown Prince and the H. R. H. Crown Princess (Lyons, 1930) received the delegates at the Royal Palace. At that time, Harold St. John Lloyd Winterbotham (UK) became Secretary General of the Union, serving until 1946.

4.5 Fifth General Assembly (17–24 September 1933, Lisbon, Portugal)

At the Fifth General Assembly (Fig. 6), the term "section" was replaced by "international association", and the associations become semi-autonomous, each responsible for specific scientific topics. Due to the great economic depression during the 1930s, the number of attendees decreased considerably compared to the GA in Stockholm in 1930; the membership dues for the coming 3 years were reduced by

Figure 5. Participants of the Fourth General Assembly (upper panel); details of the central part of the photo (lower panel) (source: IUGG archives).

one-quarter, and provision was made for further reduction in exceptional cases even though this reduction could have resulted in shrinking scientific activities of the Union Associations. Despite the world economic perturbation and the onset of political and military disturbance, the Second IPY was conducted in 1932–1933. Magnetic, auroral, and meteorological data were collected from stations located in the Arctic and Antarctic, and were used to study the phenomena associated with terrestrial magnetism and weather forecasting. Some time was dedicated at the GA to discussing these data (IUGG, 1933; SIPY, 1933). This was the last GA to be held under the presidency of Charles Lallemand (France). William Bowie (USA) was elected President of the Union.

4.6 VI General Assembly (17–25 September 1936, Edinburgh, UK)

Delegates from IUGG Member countries and guests from several non-member countries, including Austria, Germany, India, and Russia, attended the Sixth General Assembly in Edinburgh (Fig. 7). At the opening ceremony, the President of the Royal Society, the Lord Provost of Edinburgh, the Principal of the University of Edinburgh, and the President of the Royal Society of Edinburgh welcomed the delegates. The scientific work of the Union that had been conducted by the several international associations was presented at various scientific sessions. Two evening Union Lectures delivered by A. L. Day (USA) on volcanoes and by Felix A. Vening-Meinesz (the Netherlands) on gravity measurements in submarines were the first public lectures given at a GA.

Social hospitality was accorded to the Union by H. M. Government and the City of Edinburgh. Cooperation between the Union Associations was strengthened. Particularly, one step taken in this direction at the GA was to set up a special joint commission of the Associations to study the Earth's crust under the oceans. The International Association of Oceanography adopted the resolution urging a more effective collection of meteorological data over the oceans. Dan la Cour (Denmark) was elected IUGG President, serving the Union until his death in 1942. The dues for membership to the Union continued at the same level as for the period 1933–1936 (about 160 to 800 British pounds per annum according to the national population), and a substantial part of the Union's funds were divided among the seven Associations, as before (IUGG, 1936).

Figure 6. Participants of the Fifth General Assembly (upper panel); details of the central part of the photo (lower panel) (source: IUGG archives).

Figure 7. Participants of the VI General Assembly (upper panel); details of the central part of the photo (lower panel) (source: IUGG archives).

Figure 8. Participants of the VII General Assembly (upper panel); details of the central part of the photo (lower panel) (source: IUGG archives).

4.7 VII General Assembly (4–15 September 1939, Washington, DC, USA)

The Seventh General Assembly was overshadowed by the beginning of WWII. Out of 35 countries adhering to IUGG, representatives of just 20 were present; scientists of several non-member states participated in the scientific part of the GA. Meanwhile, a record number of delegates (805 including 225 non-US scientists) attended the General Assembly (Fig. 8). The US National Research Council hosted the Assembly, the first in North America, and AGU performed the duties of the organizing committee. The Honorable Cordell Hull, US Secretary of State, sent a welcoming address (IUGG, 1939; Fleming, 1940).

Preceding the Assembly, normal communication between Member countries had become impossible. By the end of August, President D. la Cour and Secretary General H. St. J. L. Winterbotham, after consulting the US Local Organizing Committee (President Richard Montgomery Field and Secretary John Adam Fleming), cabled to all Adhering Organizations that the GA would be held, but that the IUGG Executive Committee agreed that its activities would be confined to scientific matters only. It was expected that many delegates would be absent from the GA due to the war and, in fact, the whole French delegation and many of the British delegates, including Secretary General Winterbotham, were recalled back to their countries. A number of business items from the original agenda were excluded, such as discussion of administrative matters, proposed amendments of the Statutes, and the election of new officers and executive committees for the Union and its seven Associations. The existing officers continued their terms as an emergency measure. William Bowie, former President of the Union, was chosen as Acting Secretary General. The GA agreed to continue the financial management of the Union and scientific programs, so far as available funds allowed. Fortunately, IUGG (and some of the Associations) had accumulated reserves, and it was hoped that the work of the Union and its Associations could be continued until peace was restored (Fleming, 1940).

The absence of administrative business enabled the full time of the Assembly to be devoted to scientific discussion, including joint meetings among Union Associations. Scientific meetings of the GA were held in the buildings of George Washington University. There were two public lectures: "Geodesy and Mapping in the British Empire" by H. St. J. L. Winterbotham and "From the Mexican Gulf to the Arctic Sea: the Gulf Stream and its Significance" by Bjørn Helland-Hansen (Norway); 490 papers were presented during the GA (Fleming, 1940). It was agreed that the scientific discussions had been most useful and successful, and that the GA had been as valuable as it was harmonious. Nineteen resolutions were adopted by the General Assembly, to be brought to the attention of governments and institutions (IUGG Archive, 1939).

Despite the declaration of war and the fact that some delegates had to leave the GA, a good deal of scientific work was done before the closure. At the GA's closing ceremony, IUGG President la Cour said: "Now it is a reality that the Washington General Assembly of the International Union of Geodesy and Geophysics has been held and that it has been an extremely important meeting, furthering our science and showing to the world a battlefield where only victory can be recorded because even the overthrow of a theory is a victory for truth. Words are not sufficient to express our gratitude towards our hosts. I beg them to believe that we will carry away from here and forever the memory of a very happy period in our life, despite the war clouds that have gathered around us" (Fleming, 1940). At the close of the GA, US President Franklin D. Roosevelt received the Union's officers and the Association presidents (Chapman, 1939; Fleming, 1940).

During WWII, normal communication between IUGG Member countries became difficult or impossible. Although major activities of the Union and subscriptions were suspended, IUGG continued to allocate grants to support work that could be done by the Union Associations and other organizations to which it had access, and published some works during the early years of the war (IUGG, 1946). One of the problems that affected IUGG was the safeguarding of Union archives. For example, on the outbreak of war, the University of Strasbourg, France, where the IASPEI Secretariat was located, was evacuated to Clermont-Ferrand, France, taking the IASPEI's library and records along with other documents. Some of this material was deposited in a chateau in the Jura mountains, but was discovered by Germans troops and taken to Jena, Germany. At the end of WWII, IUGG tried to recover the archives through diplomatic negotiations. Another loss: many scientists active in IUGG before WWII found that they did not have time for it because of their efforts to help the post-war recovery of their national economies and sciences after the war (Greenaway, 1996).

5 Distinguished leadership

When looking at the historical development of science from Ancient Egypt to the modern world, there is no doubt that science is made by individual scholars. Similarly, scientific organizations could not be created and successfully developed without the unselfish contribution of thousands of scientists. Some of them were crucial to the formation and early development of IUGG. This section presents those who led the Union and significantly contributed to its initial development.

Charles Lallemand, the first President (1919–1933) Charles Lallemand (France, 1857–1938) was a geodesist, known for his scientific work to determine precise heights above mean sea level. He graduated from l'Ecole Polytechnique and Ecole des Mines in Paris. From 1884 until 1928 he was head of the French National Bureau of Surveying. Lallemand was the French delegate to the July 1919 meeting of the International Research Council in Brussels, during which he was elected IUGG President. He was elected to the French Academy of Sciences in 1910, and became the President of the Academy in 1926. Lallemand was also President of the Société astronomique de France (1923–1925). Lallemand was described as a personality of great charm and refinement, an expression of courtesy mingled with firmness, and a mind endowed with an admirable power of expressing its thoughts in clear and precise language (source: Perrier, 1938). (Courtesy: Academie des sciences)

Prince Albert I, the first Vice President of IUGG (1919–1922) Prince Albert I of Monaco (1848–1922) was an oceanographer and statesman. Prince Albert I devoted much of his life to the study of the sea and oceans. Being a great promoter of oceanographic science, Prince Albert I founded the Oceanographic Institute in Monaco in 1906. Following the International Geographic Congress in 1908, the International Commission for the Scientific Exploration of the Atlantic was established alongside a similar commission for the Mediterranean, and Prince Albert I became the chairperson of both commissions. Prince Albert I always had a strong interest in international cooperation. Already in 1900, he had granted his patronage to the establishment of the short-lived International Marine Association, the last meeting of which was in 1904. In 1919, when one of the IUGG Sections was assigned to Physical Oceanography, Prince Albert I took on the role of its first President (source: Smythe-Wright et al., 2019). (Courtesy: NOAA)

Sir Henry George Lyons, the first Secretary General (1919–1930) Colonel Sir Henry George Lyons (UK, 1864–1946), Fellow of the Royal Society, was a geologist. Lyons was educated at Wellington College and the Royal Military Academy, Woolwich, and at the age of 18 was elected to the Geological Society. In 1884 he was commissioned a Lieutenant in the Royal Engineers. In 1920, with the retiring rank of colonel, Lyons became director of the Science Museum in London. Lyons was elected Foreign Secretary of the Royal Society in 1928, Secretary General of the International Research Council in 1928, and the first ICSU Secretary General in 1931. Lyons played a crucial role in the formation of IUGG and its earlier development, wisely managing the Union (source: Dale, 1944). (Courtesy: Royal Society)

William Bowie, President (1933–1936) William Bowie (USA, 1872–1940) was an geodetic engineer known for scientific work in the theory of isostasy and its applications to dynamic and structural geology. He was educated at Trinity College in Hartford, Connecticut (B.S. 1893; M.A. 1907; Sc.D. 1919), and Lehigh University in Bethlehem, Pennsylvania (C.E. 1895; Sc.D. 1922). In 1895 Bowie joined the United States Coast and Geodetic Survey. During World War I he served in the United States Army Corps of Engineers as a major. He represented the United States at various international geodetic conferences and congresses. His scientific researches dealt with the theory of isostasy and its applications to dynamic and structural geology. Bowie was President of the International Association of Geodesy (1922–1933) before he was elected IUGG President. "It was a difficult matter to succeed the late Charles Lallemand who led the Union so brilliantly for fourteen years [. . .] William Bowie did add to [. . .] the significance of that post, because his geophysical interests were unusually wide and he could envisage no future in which geodesy did not work hand in glove with geophysics", wrote Winterbotham (1940). The Bowie Seamount and the Bowie Canyon are named after William Bowie. The William Bowie Medal, the highest honor of the American Geophysical Union, is named in his honor (source: Fleming, 1951). (Courtesy: US National Academy of Sciences)

Dan la Cour, President (1936–1942) Dan Barfod la Cour (Denmark, 1876–1942) was a scientist, instrument constructor, and international coordinator in geomagnetism and meteorology. Dan la Cour received his M.Sc. degree from the University of Copenhagen in 1902, and became assistant professor at the Technical University of Copenhagen in 1908. Dan la Cour participated in the Danish Meteorological Institute's (DMI) aurora expeditions to Iceland and Finland in 1899–1901, and was permanently employed at DMI in 1900. From 1903 he held various positions in DMI, becoming the Institute's Director in 1923 and keeping this position until his death in 1942. In 1925, he established the first magnetic observatory in Godhavn, Greenland, and initiated magnetic observations from Thule, Greenland, during the Second IPY. Dan la Cour served the international scientific community as President of the Scientific Commission for the Second IPY (1929–1933) and as Secretary General of the International Association of Terrestrial Magnetism and Electricity (1933–1936) before he was elected IUGG President (source: Egedal, 1942). (Courtesy: DMI)

Brigadier Harold St. John Lloyd Winterbotham, Secretary General (1930–1946) Brigadier Harold St. John Lloyd Winterbotham (UK, 1879–1946) was educated at Fettes College, Edinburgh, and the Royal Military Academy and was commissioned in the Royal Engineers in 1897. He was placed in charge of the Trigonometical and Topographical Division of the Ordinance Survey at Southampton in 1911. He returned in 1920, after duty as a military surveyor in WWI, and became Chief of the Geographical Section, contributing to texts on field surveying and the development of the Travistock theodolite. He was one of the original founders of the Field Survey Association. In 1930, he was appointed Director General of the Ordnance Survey, Great Britain's national mapping agency, retiring 1935. In 1930 he succeeded Sir Henry Lyons as IUGG Secretary General (Lyons resigned to become the IRC Secretary General) and is credited with safeguarding IUGG international interests and funds throughout WWII. He convened an Executive Committee in 1945, assisted with a radical revision of the Union's Statutes and Bylaws, and arranged for the extraordinary General Assembly in 1946 that renewed the Union (source: Cheetham, 1947). (Courtesy: Mitchell families online)

Each of these scientific leaders contributed to the development of what has become a vibrant, diverse network that traverses borders of discipline, country, language, and more. As the Union has grown and matured, its impact and reach have grown.

6 Conclusions

IUGG was formed and exists to promote international scientific research of Earth and its space environment for the advantage of their National Members, scientists, and society in general. During the period between the formation of IUGG in 1919 and the beginning of WWII, the Union grew in the number of its Member countries, increasing from 9 founding Member countries to 32. Seven general assemblies were held during this time of initial development, and the number of delegates attending the assemblies increased from a few dozen to more than 800 people, who participated in the IUGG General Assembly in Washington, DC in 1939.

IUGG coordinated and promoted scientific activities of its Sections (later Associations) during this initial period. Surveys to measure the Earth's surface in relation to the geometry of the theoretical figure of the Earth (the geoid) required sophisticated measurements of gravitational characteristics. New instruments for the measurements become available in the 1920–30s, and they could be easily transported to different regions of the world, allowing for comparative studies. New principles were introduced in many kinds of measurements, and IUGG, with its Section of Geodesy and other Sections, did valuable work in making the principles widely known. The Section of Scientific Hydrology promoted scientifically the areas of societal need, such as the production of energy, water security, irrigation, and flooding. The Section of Meteorology had fostered international codes for transmitting information about meteorological conditions, and proposed to review scientific methods of weather forecasting as applied in different countries. In the 1930s, IUGG promoted standardization of methods (e.g., for rainfall measurements) and of instruments used in different countries. The Section of Physical Oceanography promoted a collaboration between many bodies concerned with particular seas and oceans (e.g., the Mediterranean Sea, and the Atlantic and Pacific oceans). In the 1920–30s, seismologists benefited from the rapid transmission of information and data by telegraph and then by radio. The Section of Seismology encouraged national seismic services to set up seismic observatories in places prone to seismic and volcanic hazards. The Section of Volcanology promoted the importance of collecting and disseminating information, encouraging the collection of information on active volcanoes, the substances emitted, the temperature, and other characteristics of lava and hot springs. This Section drew attention to importance of the study of atmospheric dust due to volcanic eruptions as well as the importance of providing information on submarine eruptions that ships observed (Greenaway, 1996).

Although the WWII interrupted active scientific cooperation among nations, after the war, cooperation was restored and intensively developed (Joselyn and Ismail-Zadeh, 2019; Joselyn et al., 2019). The foundations of the Union offer insight into the motivations for its development; and subsequent articles in this Special Issue will explore how the organization has evolved in a changing global landscape.

Data availability. The paper is based on published documents (see a list of references) and IUGG Archive documents. The original hard-copy documents of IUGG are deposited in the Niels Bohr Library and Archives of the American Institute of Physics (AIP, 2019). The documents are accessible only in the library with permission from the IUGG secretary general.

Appendix A: IUGG Union Commissions, Working Group, and standing Committees

Table A1. Union commissions.

Climate and Environmental Change (CCEC)	Established in 2012, the CCEC provides an all-Union perspective on climatic and environmental change, making the knowledge and insights developed through scientific research available for the benefit of society and planet Earth. This commission is linked with WCRP and most recently with the Future Earth Programme as well as several international unions dealing with climate change research, such as the International Union of Biological Sciences (IUBS) and International Union of Food Sciences (IUFS).
Mathematical Geophysics (CMG)	Established as the Working Group on Geophysical Theory and Computers in 1964, the group was restructured as the Committee on Mathematical Geophysics in 1971 and was renamed as the Commission on Mathematical Geophysics in 2004. CMG aims to encourage the application of mathematics, statistics and computer science in all areas of geophysics. All IUGG Associations participate in the work of the commission. CMG has established links with the International Mathematical Union (IMU) and the International Union of Theoretical and Applied Mechanics (IUTAM).
Study of Earth's Deep Interior (SEDI)	Established in 1987, SEDI is dedicated to an enhanced understanding of the past evolution and current thermal, dynamical, and chemical state of the Earth's deep interior, and of the effect that the interior has on the structures and processes observed at the surface of the Earth. The Associations directing its work are IAG, IAGA, IASPEI, and IAVCEI. SEDI has promoted the development of an American Geophysical Union (AGU) Section with a similar title (and the groups are known as AGU SEDI Section and SEDI International).
Geophysical Risk and Sustainability (GRC)	Established in 2000, the GeoRisk Commission studies the interaction among geophysical hazards, their likelihood, and their wide social consequences due to the increasing vulnerability of societies. All IUGG Associations participate in the work of the commission. The GRC has established links with several intergovernmental and international scientific bodies such as IRDR, UNISDR, the Section on Earth Sciences and Geohazard Risk Reduction of UNESCO, and United Nations Office for Outer Space Affairs (UNOOSA).
Data and Information (UCDI)	Established in 2008, the UCDI provides a focused and sustainable organizational structure that supports and strengthens IUGG science through integrated scientific information activities. The UCDI networks with the CODATA and WDS.
Planetary Sciences (UCPS)	Established in 2015, the UCPS promotes and coordinates physical, chemical, and mathematical studies of planets in the solar system and around other stars. The UCPS has recently established a link with the European Space Agency (ESA) to promote space and planetary sciences.
Working Group on History of Earth and Space Sciences (WGH)	Established in 2012, the WGH aims to raise the historical consciousness of the membership, to help preserve IUGG scientific and institutional history, and to spearhead the effort to commemorate IUGG's 100th anniversary in 2019.

Table A2. Union standing Committees.

Capacity Building and Education	Established in 2011, this committee promotes the science education program of the Union, develops international cooperation in science education, and manages the IUGG science education grants program.
Honors and Recognition	Established in 2011, this committee oversees Union award and medal programs, including review of procedures for nominations and selection of awardees.
Statutes and By-Laws	This long-standing committee prepares modifications of the Statutes and By-laws of the Union based on the proposals for changes submitted by Member countries or the IUGG Bureau.
Visioning	Established in 2011, this committee developed and reviews the IUGG strategic plan and recommends improvements of existing Union activities and structures.

Appendix B

Table B1. IUGG programs.

International Lithosphere Program (ILP)	ILP is an inter-Union body under the auspices of IUGG and the International Union of Geological Sciences (IUGS), which is dedicated to elucidating the nature, dynamics, origin, and evolution of the lithosphere through international, multidisciplinary geoscience research projects and coordinating committees. It had been an ICSU Interdisciplinary Body since 1980, but at their General Assembly in 2005, ICSU recommended that responsibility should reside only with IUGG and IUGS. The Unions reaffirmed the ILP mission, approved new Terms of Reference, and appointed new members of the ILP Bureau.
Global Geodetic Observing System (GGOS)	GGOS is the observing system of the International Association of Geodesy (IAG) of IUGG. Established in 2003 GGOS works with the IAG components to provide the geodetic infrastructure necessary for monitoring the Earth system and global change research. GGOS aims to supply the observations needed to monitor, map, and understand changes in the Earth's shape, rotation, and mass distribution; to provide the global geodetic frame of reference that is the fundamental backbone for measuring and consistently interpreting key global change processes and for many other scientific and societal applications; and to benefit science and society by providing the foundation upon which advances in Earth and planetary system science and applications are built.
Geoscience Education Program	The development of advanced knowledge and skills of students and scientists through learning experience, study, instruction, and practical work is an essential component of the science education activities of IUGG. In 2011, IUGG and the Abdus Salam International Centre for Theoretical Physics (ICTP, Trieste, Italy) took steps to enhance geophysical education. The ICTP and IUGG agreed to promote educational programs related to geodesy and geophysics. The 8-year agreement encourages collaboration in the organization of advanced schools/workshops at the ICTP or in less-affluent countries; in the development of diploma courses related to Earth and space sciences; and in the dissemination of information on educational and scientific meetings (Ismail-Zadeh, 2016a).
Grants Program	In 2007, IUGG established the Grants Program to complement its existing program of funding scientific meetings. The Program aims to support projects of importance to the international geophysical and geodetic community, which will explore new scientific ideas and develop future international initiatives addressing an enhancement of geophysical research and Earth science education in underdeveloped and developing countries. IUGG has awarded grants to 28 projects so far.
Honor and Recognition Program	The IUGG activities would be impossible without the voluntary contributions of thousands of geoscientists creating new knowledge and working on the promotion of international cooperation. To honor distinguished scientists and outstanding young researchers, the Union and its Associations continue to develop their honor programs. IUGG established three major Union awards in 2013: the Gold Medal, Honorary Membership, and the Early Career Scientist Award. Among more than 20 medals, prizes, and awards of the Union Associations, the most important awards to senior scientists are the IAG Guy Bomford Prize, the International Hydrology Prize awarded by IAHS in cooperation with UNESCO and WMO, the IAGA Shen Kuo Award for Interdisciplinary Achievements, the Prince Albert I Medal established by Prince Rainier of Monaco in partnership with IAPSO, the IASPEI Medal, and the IAVCEI Thorarinsson Medal. Many IUGG Associations established awards for early career scientists: the IACS Early Career Scientist Prize, the IAG Young Authors Award, the IAHS Tison Award, the IAGA Young Scientist Award, and the IAVCEI George Walker Award. The Eugene LaFond Medal is awarded to an ocean scientist from a developing country for the best presentation at IUGG/IAPSO assemblies (Ismail-Zadeh, 2016a).
Publication Program	In 2012, IUGG signed an agreement with the Cambridge University Press to produce a series of works entitled "Special Publication of the IUGG". Three books have already been published (Ismail-Zadeh et al., 2014; Li et al., 2016; Beer et al., 2018).

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IUGG evolves (1940–2000)

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Abstract. The International Union of Geodesy and Geophysics (IUGG) began anew after World War II with a new governance and membership structure. The technologies developed during the war were brought to bear in the extraordinary global scientific effort that was the International Geophysical Year (1957–1958). Major changes in the geopolitical landscape have brought about further changes in IUGG's structure. International scientific campaigns encompassing multiple disciplines became commonplace, and international scientific bodies were organized and networked. During this time period (1940–1999), 15 general assemblies and 2 extraordinary general assemblies were held, each in a different international venue. Summaries of each general assembly are presented, as well as overviews of the changes in IUGG's structure, finances, membership, and publications. The scientists, who led the Union and contributed to the development of the Union, are also presented.

1 Introduction

After 2 decades of international scientific collaboration through the development and growth of the International Union of Geodesy and Geophysics (IUGG), World War II (WWII) brought the Union's activity to a standstill. In this paper, we describe the evolution of the Union for the period from the end of WWII to the end of the 20th century. The most important scientific program in the life of the Union in the 1950s was the International Geophysical Year (IGY, 1957–1958), an initiative of IUGG and some other scientific unions and national members of the International Council of Scientific Unions (ICSU), which was co-sponsored by ICSU and the World Meteorological Organization (WMO). During 1940–1999, 17 IUGG General Assemblies including two extraordinary assemblies were held in Cambridge (UK in 1946, an extraordinary assembly), Oslo (Norway, 1948), Brussels (Belgium, 1951), Rome (Italy, 1954), Toronto (Canada, 1957), Helsinki (Finland, 1960), Berkeley (USA, 1963), Zurich (Switzerland, 1967), Moscow (USSR, 1971), Grenoble (France, 1975), Durham (UK, 1977, an extraordinary assembly), Canberra (Australia, 1979), Hamburg (Germany, 1983), Vancouver (Canada, 1987), Vienna (Austria, 1991), Boulder (USA, 1995), and Birmingham (UK, 1999). Major changes in the geopolitical landscape have brought about further changes in IUGG's structure. International scientific campaigns encompassing multiple disciplines became commonplace, and international scientific bodies were organized and networked. Also, we overview the changes in IUGG's structure, finances, publications, and membership, and highlight the leaders of the Union, who contributed significantly to the promotion of international scientific cooperation during this time period.

2 IUGG 1940–1960

Though an invitation from Oslo, Norway was accepted for the proposed General Assembly (GA) in 1942; the Executive Committee had the authority to postpone "should conditions make it necessary" – an authority which they put to use. No general assemblies were held in 1942 or 1945, nor was any IUGG President shown for the years 1943–1945. Following the war, it was necessary to reinitiate the Union. This post-war revival effort was due largely to the efforts of Secretaries General Harold St. J. L. Winterbotham (UK; 1930–1946) and James Stagg (UK; 1946–1951). Even before WWII began, Winterbotham took steps "to safeguard the Union's funds and contrived to keep an emergency organisation running until the end of hostilities" (Stagg, 1947). Stagg also noted that some of the work of maintaining the organization was carried out in a distributed manner through the associations: "Some of the associations, on their side, continued their work in some measure throughout the War, supporting themselves on the annual subscriptions from their own and neighbouring countries" (Stagg, 1947). Both Winterbotham and Stagg were instrumental in post-war reconstruction, assuring the continuation of IUGG and restarting its development.

2.1 Extraordinary General Assembly (29 July–2 August 1946, Cambridge, UK)

An extraordinary GA was called in 1946 to put the Union on its post-war feet. Held in Cambridge, UK, it was attended by delegates from 16 Member countries. IUGG Statutes and Bylaws were adopted. A radical change in the method of subscription by Member countries was introduced that allowed the countries to choose one of eight categories of membership. The only proviso was that the category selected had to be formally approved by IUGG's Council, on which every country had one representative. The category of membership determined the annual dues to be paid, and the voting rights in Council discussions involving finance. Delegates to the GA also discussed and endorsed the agreement made between IUGG and the United Nations Educational, Scientific and Cultural Organization (UNESCO). By this agreement, the Union agreed to disseminate information on geodetic and geophysical subjects in countries where contacts on scientific matters were few, and in return, UNESCO agreed to promote international cooperation by financial support for publications and meetings, and geodetic and geophysical services (Stagg, 1947).

2.2 VIII General Assembly (19–28 August 1948, Oslo, Norway)

IUGG President Bjørn Helland-Hansen (Norway) could not attend the GA due to his state of health, and Vice President Niels E. Nørlund (Denmark) acted on behalf of the President. James Stagg was Secretary General. The Opening Ceremony was attended by H.M. the King of Norway and H.H. the Crown Prince. The Government of Norway, the municipality, and the University of Oslo extended generous hospitality to the Union. Two public lectures were presented: "Geophysics, Vocation or Avocation?" by Merle Antony Tuve (USA) and "The Eruption of Mount Hekla, 1947–48" by Sigurdur Thorarinsson (Iceland), who showed a color film on the volcano's eruption (Stagg, 1948). At this GA, the office of Vice President was restored, and the first Finance Committee President was named: John Tuzo Wilson (Canada). Member countries were urged to set up National Committees, if they had not already done so. Each Association held its own scientific assembly during the GA. Cooperation with the International Astronomical Union (IAU) and the International Telecommunication Union (ITU) in topics of geodetic astronomy was highlighted, as was the importance of the International Meteorological Organization (IMO) to serve as a clearinghouse for ideas and to link together the various meteorological research bodies throughout the world. The Joint Inter-Association Committee on the Physics of the Earth's Interior replaced the Union Committee on Continental and Oceanic Structure (Proudman, 1948). The Joint Committee on the Ionosphere proposed a third International Polar Year in 1957–1958. There were seven permanent services such as one on Standard Sea Water Service. IUGG was represented at the 1948 and 1950 meetings of the Pan American Institute of Geography and History (PAIGH).

2.3 IX General Assembly (21–31 August 1951, Brussels, Belgium)

President Felix Andries Vening-Meinesz (the Netherlands) presided. Vice Presidents were Sydney Chapman (UK) and Leason J. Adams (USA), and James M. Stagg (UK) was Secretary General. H.M. Queen Elisabeth of Belgium attended the Opening Ceremony. The Assembly host was the Belgian Committee for Geodesy and Geophysics, chaired by J. F. Cox. It was noted that IUGG had been "born" in Brussels 32 years prior. The attendance of 918 people at the Palais des Beaux-Arts indicates that scientific activities were once again a national priority (Fig. 1). Accounts were managed by the Secretary General and were denominated in English Pounds. The International Polar Year 1957–1958 was approved "in principle", and the immediate formation of a steering committee was urged in order to allow a full 5 years to make the arrangements. The name of the International Association of Seismology was changed to the International Association of Seismology and Physics of the Earth's Interior (IASPEI). Twenty-four resolutions were adopted by the GA (Cox, 1951).

2.4 X General Assembly (14–25 September 1954, Rome, Italy)

IUGG President Sydney Chapman (UK) presided. The Vice Presidents were Gino Cassinis (Italy) and Jacob Bjerknes (USA). Georges R. Laclavère (France) was Secretary General. The Assembly was hosted by the Consiglio Nazionale delle Ricerche (CNR). The post-WWII period in the development of international cooperation in Earth and space sciences is characterized by change in the scientific and political landscapes. The formation of the United Nations (UN) after WWII broadened the scope of the involvement of IUGG in international scientific cooperation via new scientific pro-

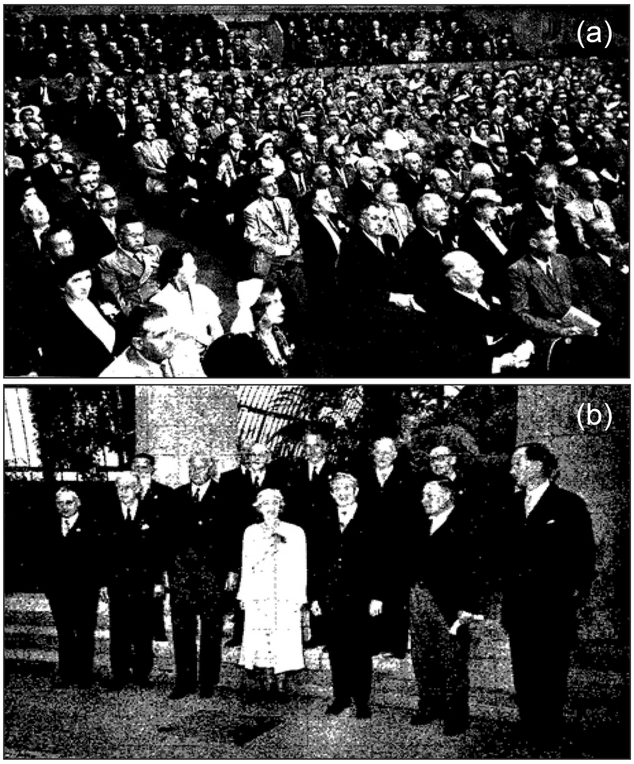


Figure 1. IX General Assembly of IUGG. **(a)** Opening Ceremony at the Palais des Beaux-Arts, Brussels. **(b)** Members of the IUGG Bureau, the Belgian National Committee for Geodesy and Geophysics, and the Association Presidents meeting H.M. Queen Elisabeth of Belgium at Château Royal de Laeken (Cox, 1951).

grams of the inter-governmental agencies, especially WMO. Its predecessor IMO was founded in 1873 to facilitate the exchange of weather information across national borders. WMO became a specialized agency of the United Nations in 1951 addressing areas of meteorology (weather and climate), operational hydrology, and related geophysical sciences. Relations between WMO and IUGG were formalized by the signing of a working agreement in 1953 whereby IUGG is recognized by WMO as the international forum for the advancement of meteorology while WMO is recognized by IUGG as having the primary responsibility for the international organization of meteorology. WMO and IUGG agreed to keep each other "advised of all developments and projected activities" within the WMO and IUGG fields of interest (WMO, 2002).

Many advances in geophysics, meteorology and ionospheric physics, ultra-high-frequency and microwave radars, jet propulsion, V2 rockets (long-range guided ballistic missiles), new techniques in nuclear physics, solar radio noise, radio astronomy, and radio aeronomy were made during WWII. While there is very little information available about the proceedings of the General Assembly, Joint Commissions reporting at the Assembly included those on Solar and Terrestrial Relationship (with IAU and the International Union of Radio Sciences – URSI); on the Ionosphere (with IAU, URSI, and the International Union of Pure and Applied Physics – IUPAP); on Oceanography (with the International Union on Biological Sciences – IUBS); and on Radio-Meteorology (with URSI). These were busy years for IUGG President Chapman, who was also the President of the Special Committee for the International Geophysical Year (Comité Spécial de l'Année Géophysique Internationale – CSAGI) set up in 1952.

The significance of the International Geophysical Year for IUGG

The International Geophysical Year (IGY) that lasted from 1 July 1957 to 31 December 1958 has a special place in the history of international scientific cooperation of the 20th century (e.g., Launius et al., 2010). "The spectacularly successful International Geophysical Year, run by the International Union of Geodesy and Geophysics, had received acclaim from the scientific world at large" (Harrison, 1978). The IGY was a remarkable project not only because of its outstanding accomplishments and the involvements of thousands of scientists, who contributed to the IGY success, but also because the year gave rise to several major international initiatives (Ismail-Zadeh, 2016).

The IGY was one of the most important global scientific undertakings in the second half of the 20th century, involving policymakers and opening a new era of Earth and space exploration. The Year was conceived during a dinner party in April 1950 at the home of James A. Van Allen, where geophysicists Sydney Chapman, Lloyd Berkner, J. Wallace Joyce, Ernest Vestine, and S. Fred Singer met. The initial aim was to create a third International Polar Year, 25 years after the second IPY (1932–1933), coinciding with the time of solar maximum. In January 1951, IUGG and ICSU endorsed Berkner's proposal to launch a third IPY. Later, at a session of the IX IUGG General Assembly held in Brussels, Belgium, on 23 August 1951 and chaired by IUGG President Sydney Chapman, Johannes Egedal, a Danish meteorologist, argued vigorously that "observations … should be taken all over the earth", and especially at the Equator as well as at the poles (Bulkeley, 2008). This idea was supported by WMO, whose historical predecessor – the International Meteorological Organization – had launched two previous International Polar Years. Egedal suggested then to Chapman to change the name of the Year from "Polar" to "Geophysical", and Chapman agreed. The change was endorsed then by ICSU in 1952, and the scope of the International Geophysical Year was broadened to involve all parts of the globe and all branches of the Earth and space sciences (Bulkeley, 2008). The first international planning meeting for the IGY, with 26 nations participating, occurred in 1953. In September 1954, an IUGG resolution, soon backed by CSAGI, called for a

Figure 2. Stamps dedicated to the IGY and produced by the USA (the upper left stamp), Norway (the upper right stamp), and the Soviet Union. The texts in Russian of the Soviet stamps read "The pioneer artificial Earth satellite launched by the Soviet Union" (the lower left panel) and "According to the International Geophysical Year program, the Soviet Union launched on 15 May 1958 the third artificial Earth satellite of 1327 kg to a height of 1880 km" (the lower right panel). The images of the stamps are from the Internet (https://www.mysticstamp.com/Products/United-States/1107/USA/\T1\textbackslash#, https://colnect.com/es/stamps/stamp/48850-International_Geophysical_Year-International_Geophysical_Year-Noruega, https://en.wikipedia.org/wiki/Sputnik_1\T1\textbackslash#/media/File:Sputnik-stamp-ussr.jpg, and https://zvonmoneta.ru/mark-2586, last access: 30 January 2019).

satellite program to place instruments in Earth orbit (Sullivan, 1961).

The IGY's impact can be measured in several ways. First, a staggering number of scientific advancements were achieved during the 18-month period. Ultimately involving some 60 000 scientists from 67 nations, the IGY, through numerous installations and field expeditions, made possible the synoptic collection of observational data on an unprecedented global scale. It emphasized a data-driven style of research, stimulated new graduate training programs, helped establish Earth science programs in many developing and newly independent countries, and made IUGG assemblies a key venue for coordinating and communicating scientific investigations. The IGY made possible a great number of scientific advancements. For example, the 1957 launch of Sputnik by the USSR initiated the Space Age (Fig. 2). The Special Committee on Ocean Research (SCOR – later renamed the Scientific Committee on Ocean Research to reflect its more permanent status) was established in 1957 to address interdisciplinary science questions related to the ocean. Associated with the IGY, a number of interdisciplinary scientific bodies were established in 1958, including the Committee on Space Research (COSPAR) and the Scientific Committee on Antarctic Research (SCAR). The IGY provided a model and inspiration for the Upper Mantle Project, the International Indian Ocean Expedition, and the International Years of the Quiet Sun. The World Data Center system, created to safeguard and share IGY data, reflected a shared desire for scientific internationalism (Aranova et al., 2010; Collis and Dodds, 2008; Korsmo, 2007).

Second, the IGY had a profound effect on geopolitics, and it deeply reflected the politics and political realities of the Cold War from which it emerged (Needell, 2000). Virtually all fields of geophysics became important to military leaders in the aftermath of WWII, as effective utilization of guided missiles and submarines required greatly expanded knowledge involving physical oceanography, terrestrial magnetism, isostasy, seismology, meteorology, ionospheric physics, and solar–terrestrial relationships. IGY architect Lloyd Berkner had written a secret supplement to a high-level report on international science he prepared for the U.S. State Department when the IGY was conceived that stressed the importance of international scientific contacts for intelligence-gathering – and IUGG assemblies in the 1950s and 1960s included covert intelligence agents. IGY research was also valued for providing useful environmental sciences data about the Arctic (deemed a potential East–West battleground, positioned dead center between the USA and the Soviet Union). At the same time, Antarctica was established as a continent for science, resolving long-standing sovereignty claims. Cold War tensions limited national involvement in the IGY (for instance, mainland China ultimately did not take part) and kept certain data from reaching the international data centers. When existing global seismic stations were augmented to create the World-Wide Standard Seismographic Network crucial for verifying the Limited Nuclear Test Ban Treaty of 1963 – a natural extension of IGY-style programs – it was a further reminder that the IGY was simultaneously a triumph of scientific internationalism and an undertaking made possible by national funding decisions reflecting Cold War anxieties (Korsmo, 2007).

Third, the IGY had demonstrated the importance of science diplomacy. By the early 1950s, the Soviet Academy of Sciences did not participate in the activities of almost all international scientific unions coordinated by ICSU, and hence Soviet scientists were not involved in the IGY initial planning. IUGG Secretary General Georges Laclavère expressed that the participation of the Soviet Academy would be essential for the influence of CSAGI to become truly global (Bulkeley, 2008). IUGG President Sydney Chapman recalled that the initial steps taken by IAU and WMO (where the Soviet Union had representatives) to attract the Soviet Union to the IGY led to no result (CSAGI, 1958). In 1952 and 1953, ICSU and IUGG sent several invitations to the Soviet Academy of Sciences to join the IGY. Although several top scientists, including the Academy's President Alexander Nesmeyanov, worked hard to join the IGY program and IUGG, until the death of the leader of the Soviet Union Josef Stalin in March 1953 and consequent political changes, no response to the invitation was received by ICSU. In early 1954, the Soviet Academy decided to take part in the IGY, and also to join IUGG; Nesmeyanov sent Chapman the first indication that this was about to happen. The Soviet Academy's decision in favor of the IGY and IUGG was a part of a larger process of the post-Stalin perestroika and science diplomacy efforts (Bedritskii et al., 1997; Bulkeley, 2008).

2.5 XI General Assembly (3–15 September 1957, Toronto, Canada)

IUGG President Kalpathi Ramanathan (India) presided. Other members of the Bureau were J. Tuzo Wilson (Canada), the solitary Vice President, and Secretary General Georges R. Laclavère (France). The General Assembly, the second in North America, was hosted by the National Research Council (NRC) of Canada (the Canadian National Committee for Geodesy and Geophysics) and the University of Toronto. The Prime Minister of Canada, John G. Diefenbaker, and the President of the NRC, Edgar W. R. Steacie, greeted the delegates from more than 50 countries. Public lectures were given by ICSU President Lloyd V. Berkner on "Scientific Aspects of the Instrumented Earth Satellite" and by Yevgeny I. Tolstikov on "The Arctic and Antarctic Program of the IGY".

At this GA, the Statutes and By-laws of the Union first adopted in 1946 were revised; for the first time, IUGG Bureau members were elected. The Bulletin, begun by Laclavère in 1952, was split into two publications in 1956. The Chronicle, containing information about programs and proceedings, began in May 1957; and scientific articles were published separately. An International Journal of Geodesy and Geophysics was proposed (but never happened), as was an International Bibliography of Geophysics and a Directory of Geodesists and Geophysicists. Already there was concern to engage larger numbers of young scientists in IUGG activities. The International Association for Terrestrial Magnetism and Electricity (IATME) became the International Association for Geomagnetism and Aeronomy (IAGA; note that an initial suggestion was the International Association for Geomagnetism and Physics of the Ionosphere). A committee was formed by the International Association of Geodesy (IAG), IAGA, and IASPEI to organize the World Magnetic Survey. There were inter-Association (joint) commissions on the Upper Atmosphere (International Association of Meteorology – IAM and IAGA) and Atmospheric Electricity (also IAM and IAGA).

Planning for the IGY was a priority during the period. Particularly, IUGG (along with URSI and IAU) had an important role in establishing the Federation of Astronomical and Geophysical Permanent Services (FAGS) in 1956, funded substantially by UNESCO. Some of the nine permanent services and their related Associations were the International Gravimetric Bureau (of IAG), the Bureau for Geomagnetic Indices (of IAGA), and Mean Sea Level (of the International Association of Physical Oceanography –IAPO). IUGG became a member of SCOR as well as the Joint Commissions on Solar-Terrestrial Relationships; the Ionosphere; Radio-Meteorology; and Applied Radioactivity. ICSU initiated a Special Committee on the Biological Effects of Nuclear Radiation. IUGG began attending meetings of the Cartographic Office of the UN in 1955. A permanent liaison was established with PAIGH in 1954 and WMO in 1957.

Twenty-three Union resolutions were published in French, English, and Russian (IUGG Archives, 1957). They dealt with issues concerning combined membership of the German national committees, the Chinese national committees, and Cuba; adoption of a standardized value for the speed of light; the need and methodology for geodetic and gravity measurements; the need to deep drill into ocean sediments and further into the Mohorovicic discontinuity; that ICSU restore a budget cut to the International Seismological Summary; that improved observations and analysis of atmospheric ozone be supported; that countries use alternating current electric power because direct current for railways hinders geomagnetic measurements; that the World Magnetic Survey be supported and the data published; that a permanent Service on the Variations of Mean Sea Level be created; that quantitative data on chemical substances dissolved in water from land surfaces be collected; and that volcanoes be reported, rocks collected, and volcanic gasses analyzed.

2.6 XII General Assembly (26 July–6 August 1960, Helsinki, Finland)

IUGG President J. Tuzo Wilson (Canada) presided. Vice Presidents were Vladimir V. Beloussov (USSR) and Wikko Heiskanen (Finland), Secretary General Georges R. Laclavère (France) and members George Deacon (UK), J. Wallace Joyce (USA), and Tsuji Chuboi (Japan). The Government of Finland and University of Helsinki hosted the Assembly. The President of the Republic and the Minister of Education attended the Opening Ceremony. The GA was attended by scientists from 58 member countries and observers from 10 non-member countries.

Finances were a major concern of the IUGG Council. President Wilson noted that there were fair income and adequate reserves in 1948. But, in the meantime, the number of members had increased and so had costs for added programs and publications (half of the Union's work was publications). Dues were increased, and the IUGG Statutes and By-laws were revised to include the office of Treasurer. A nominating committee was defined. Countries not paying dues would not receive free publications, and the Council could decide to terminate membership. Voting rules were prescribed: all delegates had one vote on the topics of scientific matters, paid-up members could vote on administrative matters, and the number of units of membership was counted for financial matters. There would be a General Assembly every 3 years. The new Statutes and By-laws were printed in French, English, and Russian.

The inter-Association bodies were Geophysical Bibliography; Upper Mantle Project; Tsunami; and the Committee on Space Research (CSR). The IUGG CSR was a response to COSPAR, the ICSU Committee on Space Research, which seemed to be encroaching on IUGG interests and expertise. The Committee on Geophysical Bibliography decided to employ existing Bibliographic services, and dissolved. IUGG endorsed the ICSU Policy on non-discrimination. Three International Scientific Unions (IUGG, IAU, and IUPAP) supported ICSU's Special Committee for Geophysics (Comité Internationale de Géophysique – CIG). The CIG approved three projects: the World Magnetic Survey, the Upper Mantle Project, and the International Years of the Quiet Sun. ICSU also approved the constitutions of the Inter-Union Committees on Radio Meteorology (IUCRM), on the Ionosphere (IUCI), and on Solar Terrestrial Relationships (IUCSTR). FAGS acquired two new services: the International Time Bureau (Bureau International de l'Heure) and General Bathymetric Chart of the Oceans.

Twenty-one Union resolutions were passed (IUGG Archives, 1960). They concerned the IUGG Publication office; that metric units were recommended for use in all scientific papers; that the Committees on Space Research, Near Shore Oceanography, Meteorology of the Upper Atmosphere, and Dynamical Meteorology should be formed; that there should be increased support for the International Latitude Service and that a permanent service should be established on the General Bathymetric Chart of the Oceans; that meteorological data should be made available for research; that the Tsunami Committee should establish a warning system; that lunar influences on geophysical processes should be investigated; that a document, "Codification of rules for protection from Volcanic eruptions", should be printed and distributed, as well as a quarterly "Bulletin of Volcanic Eruptions"; that seismological research be done in central and South America and eastern Europe, and that a catalog of earthquakes from 1801 to 1900 be prepared; that programs of gravity measurements should be accelerated; and that satellites with flashing lights and devices for electronic tracking be launched.

3 IUGG 1960–1999

The period of time between the 12th General Assembly (1960) and the 22nd General Assembly (1999) was marked by profound shifts, both scientifically and politically. The legacies of the IGY and the realization that the best scientific outcomes come from both international and interdisciplinary cooperation extend to today. The discoveries in Earth and space sciences (e.g., the extent and morphology of Earth's magnetic field) and the observations of Earth as a planet have irrevocably shaped every discipline within the IUGG purview. Simultaneously, geopolitical forces reshaped the geographic landscape. A comparison of the 58 national Members adhering to IUGG in 1963, with the 76-Member roster in 1999, shows the growth in the number of Member countries of the Union (Appendix A). 49 Members remained, some had relinquished membership, three had ceased to exist as a single entity (Czechoslovakia, USSR, and Yugoslavia), and "new" countries had appeared. Thirteen of those had not existed in 1960, and the others were countries that had built the capacity to take their rightful place in geophysical society. Twelve other countries were briefly members during those 36 years. These countries acquired membership after 1963, but were removed from the membership list before 1999; examples are the Democratic Republic of Germany, and the Republic of China, whose memberships were cancelled because of the reunification of Germany in 1990, and the admission of the People's Republic of China in 1977, respectively. These were a noteworthy 39 years of global as well as IUGG history.

3.1 Inter-Union Scientific Campaigns and Programs

Throughout this time of evolution, IUGG was strongly guided by ICSU as well as by developing relationships with other governmental and non-governmental national and international bodies. While these relationships are introduced chronologically in Table 1, the major inter-Union programs of interest to IUGG are summarized first. These programs illuminate the overarching geophysical scientific focus through these years.

Throughout the years, the Associations and inter-Association bodies have sponsored numerous topical scientific symposia, many intentionally convened in developing countries. The records of the Union list these symposia that educated and promoted progress in the various disciplines of study. IUGG often provided support for these meetings, especially to ensure the attendance of young scientists and those from financially disadvantaged countries.

3.2 IUGG Structure

There were several proposals to radically change IUGG between 1960 and 1999. At the 1963 GA held in Berkeley, California, USA, President Joseph Kaplan initiated extended discussion of the future of IUGG, then 44 years old. The growing attendance at the General Assemblies was one of the main issues, and it was also an important consideration in the scheduling of the next Assembly, because no bid had been received. A special meeting of the Council was held to consider possible reorganization. As a result, two committees

Table 1. International Scientific Programs and IUGG involvement.

World Magnetic Survey (WMS; 1958–1969)	Sydney Chapman (IUGG President, 1951–1954) proposed the WMS to the ICSU Special Committee for the IGY to address the need for data for theoretical studies of the source and origin of the Earth's magnetic field and its secular changes, and to prepare more accurate world magnetic charts for purposes of navigation. IAGA was primarily responsible for this program and wrote the "Instruction Manual on WMS," published as an IUGG monograph in 1961. The data collected were archived and exchanged by the ICSU World Data Centers (now the ICSU World Data System).
International Years of the Quiet Sun (IQSY; 1964–1965)	The IQSY was established by the ICSU Comité Internationale de Géophysique (CIG) to coordinate observations and studies of solar activity and related geophysical phenomena conducted at a time of minimum solar activity. Observations were conducted at a large number of solar, magnetic, ionospheric, auroral, cosmic-ray, and other stations, as well as onboard artificial satellites and sounding rockets. IAGA contributed significantly to this program; the data taken under the period of the IQSY were archived in the ICSU World Data Centers.
International Years of the Active Sun (IASY; 1968–1971)	Following on from the success of the IQSY and its established international observational networks, IUGG and particularly several IAGA Commissions supported this inter-Union ICSU program of multi-disciplinary observations of solar activity and related geophysical phenomena. The program was further extended through the following solar cycle as a special project for monitoring of the Sun–Earth environment.
Upper Mantle Project (UMP; 1964–1970)	This international program of research on the solid Earth was coordinated jointly by IUGG and the International Union of Geological Sciences (IUGS) and included the active participation of all interested ICSU Unions and Committees. UNESCO participated by initiating an international project for the study of the East African Rift System.
International Hydrological Decade (IHD; 1965–1974)	Launched by UNESCO, the IUGG International Association of Scientific Hydrology (IASH; now IAHS) was an effective partner in formulating programs, contributing to the activities of working groups, and convening IHD symposia. UNESCO provided a platform for discussion of practical problems of hydrology and water resources development. Léon Jean Tison (IAHS Secretary General, 1948–1971) is recognized as one of the three "fathers" of the IHD, which became the foundation for ongoing global research on water sciences and management.
International Hydrological Programme (IHP; 1975–ongoing)	An outgrowth of the IHD, this UNESCO intergovernmental program facilitates an interdisciplinary and integrated approach to watershed and aquifer management, which incorporates the social dimension of water resources, and promotes and develops international research in hydrological and freshwater sciences. IAHS and the International Association of Cryospheric Sciences (IACS) maintain close contacts with the UNESCO-IHP.
International Geodynamics Project (GDP; 1972–1979)	The GDP was a joint IUGG/IUGS program of ICSU that addressed the solid Earth but paid special attention to the uppermost part of the Earth. The GDP was recognized as the beginning phase of a new approach to the scientific understanding of the solid Earth. This successful program spawned the Inter-Union Commission on the Lithosphere approved by ICSU in 1980 to implement the international program "Dynamics and Evolution of the Lithosphere: The Framework for Earth Resources and the Reduction of Hazards". IUGS and IUGG Associations IASPEI and IAVCEI carried out the scientific work of the project.
Scientific Committee on the Lithosphere (SCL/ILP; 1980–2005); International Lithosphere Program (ILP; 2005–ongoing)	Established by ICSU at the request of IUGG and the IUGS, the program aims to understand the origin, dynamics and evolution of the lithosphere through international multidisciplinary research projects. In 2005, ILP became an Inter Union programme of IUGG and IUGS.
Global Atmospheric Research Programme (GARP; 1967–1980)	In 1967, the UN General Assembly formally invited ICSU to work alongside the WMO to develop a program of atmospheric research in response to developments in space technology. This international research program organized several important field experiments including GARP Atlantic Tropical Experiment in 1974. The GARP experiments contributed to the progress in meteorology and, particularly, in numerical weather prediction.

Table 1. Continued.

World Climate Research Programme (WCRP; 1980–continuing)	The successor to GARP, WCRP is the major mechanism for the coordination and promotion of climate science and its applications. In 1979, Bert Bolin, a Swedish meteorologist and IUGG Bureau Member (1963–1967), led a group of scientists to set up the WCRP to determine whether the climate was changing, whether climate could be predicted, and whether humans were in some way responsible for the change. The program, established in 1980, was co-sponsored by ICSU and WMO. Since 1993, it is also co-sponsored by the Intergovernmental Oceanographic Commission (IOC) of UNESCO. WCRP core research projects (Global Energy and Water Exchange (GEWEX), the Climate and Ocean Variability, Predictability and Change (CLIVAR); the Stratosphere-troposphere Processes and their Role in Climate (SPARC), and Climate and Cryosphere (CliC)) are of particular interest to IUGG Associations and the Union Commission on Climatic and Environmental Changes (CCEC).
Middle Atmosphere Program (MAP; 1982–1990)	MAP was originally an interdisciplinary program under the ICSU Scientific Committee on Solar Terrestrial Physics (SCOSTEP) known as SESAME – Structure and Energetics of the Stratosphere and Mesosphere. The International Association of Meteorology and Atmospheric Physics (IAMAP, now IAMAS) and IAGA made substantial scientific contributions to this study of the stratosphere and mesosphere with the lower ionosphere, areas not covered by GARP.
International Geosphere-Biosphere Programme (IGBP; 1987–2015)	Throughout the 1980s, evidence mounted that climate change was one part of a larger phenomenon – global change – requiring an even wider scientific view and connections among geophysics, chemistry and biology. In 1987, a team of researchers again led by Bert Bolin and others, successfully argued for an international research program to investigate global change. IGBP was launched to address the Earth as a system of globally interacting phenomena, including understanding the processes that regulate and change this system, and the role of human activities in affecting global change. IUGG contributed to the program through IAMAS and IAPSO. In 2015, the scientific projects and networks under IGBP transitioned into Future Earth, a major environmental program network.
Intergovernmental Panel on Climate Change (IPCC, 1988–continuing)	The IPCC was launched in 1988 to independently assess the scientific results provided by WCRP and IGBP projects as well as assessment reports by IPCC panels. Burt Bolin and his colleagues were instrumental in arguing for the establishment of the IPCC. Several IUGG scientists shared the Nobel Peace Prize awarded to IPCC in 2007.
International Decade for Natural Disaster Reduction (IDNDR; 1990–1999)	Launched by the United Nations, the program was succeeded by the UN International Strategy for Disaster Reduction (UNISDR). A major achievement of the IDNDR was the Global Seismic Hazard Map, an IASPEI project. To promote participation in the IDNDR, IUGG created a Committee for Problems of the International Decade for Natural Disaster Reduction that evolved into the Commission on Geophysical Risk and Sustainability (GRS) in 2000.

were named; a "Committee of 4" composed of four people appointed by the incoming President; and a "Committee of 14" composed of 14 people (7 people were appointed by Associations, each of them had one representative in the committee, and 7 people were appointed by the IUGG Council) and this committee did not include members of the Bureau. Each IUGG National Committee and each IUGG Association was requested to submit recommendations for consideration to the first committee. In the fall of 1964, the "Committee of 4" issued a report with an appendix that included copies of all material submitted by National Committees and Associations. In January 1966, the "Committee of 14" met in Paris and affirmed that any reorganization should preserve the autonomy and freedom of action that the Associations had always enjoyed. The "Committee of 14" then issued four Resolutions (Table 2).

The second major attempt at IUGG reorganization came on the heels of Resolution 4. COSPAR, established by ICSU in 1958, enabled ongoing international and interdisciplinary cooperation among the scientific investigations carried out with space vehicles, rockets and balloons. However, several of the ICSU Unions (IUGG, IAU, the International Union of Pure and Applied Physics (IUPAP), and URSI) laid claim to these new observations and developing science. To address the rising conflicts, ICSU formed the Inter-Union Commission on Solar-Terrestrial Physics (IUCSTP) in 1966, replacing a former Joint Committee on Solar-Terrestrial Relationships formed in 1958. However, URSI, IAGA, and IUCSTP were each addressing the same external geophysics (primarily the division between internal and external geomagnetism), and a committee was established to consider reorganization of parts of ICSU to address these conflicts. Marcelle Nicolet, President of IAGA, represented

Table 2. Four resolutions by the "Committee of 14".

Resolution 1	The resolution concerned the structure of the General Assemblies themselves. It was recommended that science meetings be confined to joint sessions of two or more Associations (interdisciplinary); that the program of meetings and the selection of topics for discussion should be decided by the Executive Committee of the Union well before the time of the General Assembly; and that meetings should consist of a number of invited papers followed by a number of submitted short papers. Associations could arrange assemblies of their own between General Assemblies of the Union, with the approval of the Union Executive Committee. It was also determined that General Assemblies should be held henceforth every 4 (not 3) years.
Resolution 2	The resolution recommended that IASPEI should focus on the physics of the Earth's interior and that IAV should be renamed the International Association of Volcanology and Chemistry of the Earth's Interior to especially include the chemistry of the Earth's interior and geochronology.
Resolution 3	The resolution concerned the composition of the Executive Committee and recommended that a nominating committee be formalized in the Statutes.
Resolution 4	The resolution took note of an ICSU action to set up an inter-Union commission dealing with solar–terrestrial relations that appeared to duplicate many of the interests of IUGG Associations.

IUGG in the negotiations and in March 1970 a proposal was offered that would combine the present responsibilities of IUCSTP, URSI, IUGG into nine "associations" that would cover, without duplication, the separate responsibilities of (i) Radiophysics, (ii) Geomagnetism, (iii) Aeronomy, (iv) Geodesy, (v) Seismology, (vi) Volcanology, (vii) Meteorology, (viii) Oceanography, and (ix) Hydrology. It was proposed that these units could be then federated into one, two, or three separate Unions within ICSU. However, at the 1971 IUGG General Assembly in Moscow, the IUGG Council received word that URSI had rejected all of the proposals including the ideas of federation. In 1972, ICSU changed IUCSTP to a Special Committee for the purpose of coordinating short-term programs requiring the cooperation of several ICSU bodies and the direct participation of national groups. In 1978, IUCSTR became an ICSU Scientific Committee on Solar Terrestrial Physics (SCOSTEP), to which IUGG maintains a liaison to the present day.

At the 1975 GA in Grenoble, France, a subcommittee under the control of the Bureau was formed to consider IUGG's structure. A "radical" reorganization of IUGG was proposed in the late 1980s, in which IUGG would be divided into two "Super-associations", one for the fluid Earth (International Association of Hydrological Sciences (IAHS), the International Association of Meteorology and Atmospheric Physics (IAMAP), the International Association of the Physical Sciences of Oceans (IAPSO), and parts of IAGA) and the other for the solid Earth (IAG, IASPEI, the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), and other parts of IAGA). These two "Super-associations" would operate independently of each other, with general guidance from the Union. The idea was rejected by IAGA because splitting IAGA into fluid Earth and solid Earth parts would not accommodate the study of planets. Furthermore, the interests of the National Members might not be served under this arrangement and the notion was discarded.

In 1989, President Vladimir Kellis-Borok convened an Advisory Board on Scientific Policy to look at the goals of the Union and make recommendations concerning its missions and objectives. In 1991, the Board was expanded to include the Presidents of the Associations and was chaired by IUGG Vice President Peter J. Wyllie. The Board gave a report at the 1995 GA in Boulder, Colorado, USA, and proposed revisions to the Statutes.

The composition of the Union officers has changed over the years. In 1960, there were two Vice Presidents and two Bureau members in addition to the President, Secretary General, and the Treasurer (begun after the 1957 GA in Toronto, Canada). The Executive Committee consisted of the Bureau, the immediate Past President, and the Presidents of the Associations (Associations Secretaries General could attend in an advisory capacity). At the 1971 GA in Moscow, the IUGG Statutes were modified such that the Bureau consisted of the President, one Vice President, Secretary General, Treasurer, and three members. At the same GA, there was a suggestion from the United States that IUGG should establish a permanent Secretariat but the proposition failed. At the 1995 GA in Boulder, the role of the Past-President was changed from a voting to a non-voting member, so that the Bureau could not out-vote the Associations in Executive Committee meetings. The procedures for nominations for Union officers were clarified at the 1999 GA in Birmingham, especially with regard to nominations at the time of the General Assembly.

Over time, there has been natural tension between the Associations and the Union, with respect to the autonomy of the Associations and the benefits of being a common Union. Such tension has risen at certain times and has been resolved at others. At the 1971 GA in Moscow, it was noted that several Associations had held their own assemblies and elected officers. This had not been visualized as a possibility, but it seemed not to cause difficulties. At the 1979 GA in Canberra, the IUGG By-law stating that Associations could not hold their own scientific sessions during IUGG General Assemblies was removed. Beginning after the 1983 GA in Hamburg, a review of the Associations was initiated. A "Fluid Earth Sciences Committee" was established in 1991, comprised of the Presidents of IAMAP, IAHS, and IAPSO and chaired by the IUGG President; it was disbanded in 1995. IAPSO did not attend the 1995 GA in Boulder, Colorado, USA, choosing instead to meet separately in Hawaii. At the 1995 GA in Boulder, it was agreed that there would be no Association sessions during Union Lectures. Following this GA, the concerns and tensions between the Associations and the Union, including any possibility of splitting the Union into "solid" and "fluid" parts, were reconciled.

3.3 IUGG finance

Since 1946, the Union has been funded primarily by payments by its National Members according to category of membership (which carry prescribed numbers of units). Associations are funded by subventions from the Union as well as by grants and direct support for specific programs from ICSU, UNESCO, and other bodies. Needless to say, the finances of IUGG, especially in terms of the price of a unit of membership and the distribution of funds to the Associations, have been under constant discussion.

IUGG finances were kept in British pounds until 1960; after that the accounts were denominated in US dollars. In 1963, the IUGG Council decided that a Member Country could raise its category of membership unilaterally, but that a vote of the Council was required to reduce it. At the 1971 GA in Moscow, the unit of membership was increased to USD 600, and there was considerable discussion about how IUGG funds were allocated to the Associations. At the 1975 GA in Grenoble, the unit of subscription was raised to USD 800 effective in January 1977. Regarding financial allocations to the Associations, it was decided that IAG and IAGA would be considered large associations and should receive equal annual allocations of approximately USD 19 000; IASPEI, IAMAP, and IAPSO medium-sized associations that should receive equal annual allocations of approximately USD 14 000; and IASH and IAVCEI two small associations that should receive equal annual allocations of approximately USD 10 000. At the 1983 GA in Hamburg, due to a worsening financial outlook, the allocations to the Associations were reduced by 20 %, and it was decided, amid strong objections from some national members, to raise the IUGG dues to USD 850 in 1985 and then to USD 900 in 1986. In 1983, the GA in Hamburg approved two higher categories of membership (11 and 12, with 35 and 40 units, respectively). By the 1987 GA in Vancouver, the finances of the Union were deemed acceptable and the value of a unit, USD 900, was maintained as were the allocations to the Associations. The GA registration fee came under discussion as being too high (the Vancouver GA ended with a small surplus). At the 1991 GA in Vienna, the IUGG Council decided to raise the unit of membership annually in 10 % steps up to USD 1200 in 1995, and the Finance Committee moved that USD 20 be added to the registration fee for the next GA and then distributed to the Associations on the basis of participation. At the 1995 GA in Boulder, the Council decided to automatically increase the unit of subscription annually based on the OECD consumer price index.

Registration fees and financing of the General Assemblies became an issue at the 1995 GA in Boulder. At this assembly, fees for attending just 1 week of what was normally a 2-week Assembly were introduced, but there was no Geohost program – a pool of money from which the registration fees of scientists from developing countries could be paid. It had been thought that support could be found for scientists from the former Soviet Union but that failed to happen. The American Geophysical Union (AGU) reported a deficit for the Boulder Assembly and the invitation for the 1999 Assembly in the UK came with a condition: the UK did not want to accept financial responsibility. Ultimately, the issue was resolved through special arrangements, including the formation of an Oversight Committee. The 1995 GA resolved that detailed invitations must reach the Secretary General not later than 3 months before the GA preceding the GA of the invitation, and should include efforts to subsidize travel, registration fees, and other expenses of scientists from developing countries and of young scientists from all countries. At the 1999 GA in Birmingham, the IUGG Council resolved that the host countries for general assemblies should henceforth carry the financial burden. A memorandum, "On invitations for IUGG General Assemblies", was developed.

3.4 IUGG publications

Early in its history, IUGG spent much of its money on publications, which it deemed to be a major responsibility. Georges Laclavère (Secretary General, 1951–1963) directed for many years the Publications Office of the Union hosted by the Institut Géographique National. The Office published the Chronicle beginning in 1957 as well as monographs (21 were published between 1960 and 1963; the first one was "Seismicity of Europe" produced in June 1960). The Chronicle was free to members (four copies/unit of membership) for personal use; otherwise, there were paid subscriptions, especially by libraries. The costs of publishing the Chronicles as well as other scientific papers became such that at the 1971 GA in Grenoble, it was decided to discontinue the publishing of monographs. In addition, a committee chaired by Georges Laclavère was appointed to consider the future of the IUGG Publication Office because his retirement from his former government post would limit the facilities available to him. By 1981, the IUGG directory (the Yearbook) was published every 4 years as one or two issues of the Chronicle. The Yearbook for 1989 was published as Chronicle issues 195–196, but also on a diskette. The Publications Office closed in 1990. Former IUGG Secretary General Paul Melchior (1973–1991) continued the Chronicles from his office in Belgium until publication ceased in 1995.

3.5 IUGG membership

At the conclusion of the 1999 GA in Birmingham, the Union had three categories of membership: Regular (with the right to vote), Observer, and Associate, but this had not always been the case. Until 1991, a National Member either paid its dues or it was not a member. In 1991, an Observer category was defined for Member countries whose payments were temporarily in arrears. Associate membership was added at the 1999 General Assembly. As a result of these options, the membership in the Union changed annually as countries either met the qualifications of membership, changed category, or departed from membership. One special case was that of the Federal Republic of Germany (FRG) and the German Democratic Republic (GDR). The FDR joined in 1951; the GDR applied for membership in 1952 and at the IUGG General Assemblies in 1957, 1960, and 1963 they shared a vote. In 1967, the GDR acquired independent membership. At the end of 1990, the GDR and FRG reunited, so the number of Member countries decreased by one. Another special case was that of the memberships of the Republic of China (ROC) and the People's Republic of China (PRC). This case resulted in an Extraordinary General Assembly in 1977, described in more detail below. At that time, the PRC replaced the ROC; in 1995 the IUGG Statutes and By-laws were revised to permit two Adhering Bodies for China.

Before 1979, all of the attendees of the General Assembly had been asked to approve the decisions of the Council. But that was removed and replaced by a requirement for a plenary session that has been subsumed into the Opening and Closing Plenaries. Also in 1979, a provision was added that the Council could be convened between General Assemblies if requested by a simple majority of the Executive Committee. In 1983, voting rules, especially with regard to a quorum and the numbers needed for a positive outcome, were added to the By-laws.

4 Highlights of IUGG General Assemblies (1963–1999)

4.1 XIII General Assembly (19–31 August 1963, Berkeley, California, USA)

IUGG President Vladimir V. Beloussov (USSR) presided. Vice Presidents were Julius Bartels (F. R. Germany) and Joseph Kaplan (USA); Georges R. Laclavère (France) was Secretary General and Maharajapuram S. Krishnan (India) and Takesi Nagata (Japan) were Bureau Members. The US National Academy of Sciences issued the invitation. The Assembly was co-hosted by the US National Committee for IUGG (Tom Malone, Chair) and the University of California. The American Geophysical Union handled the general arrangements, and David K. Todd of University of California led the Local Organizing Committee. Harrison Brown, Foreign Secretary of the National Academy of Sciences, spoke and a welcoming message from US President John F. Kennedy was read. Jerome Wiesner, Director of the Executive Office of Science and Technology, addressed the Opening Ceremony. Participation in the General Assembly was enhanced by an International Symposium on the IGY, held at the University of California at Los Angeles preceding the assembly.

The Council received the first Treasurer's report. Reports were received from the Tsunami Commission as well as from FAGS and the liaisons to SCAR, SCOR, and COSPAR. A special committee was appointed to clarify rules for admission of new countries, especially applications from the ROC and the GDR. Other IUGG scientific committees included those on Geophysics Bibliography, Space Research, the Upper Mantle Project, the International Hydrographic Decade, Problems of Geochemistry, and an Inter-Association Heat Flow Committee. IAG changed its organizational structure as a result of the availability of artificial satellites for geodetic applications.

Representatives were named to the Inter-Union Commission on the Ionosphere (IUCI), replacing the Mixed Commission on the Ionosphere (dissolved in 1958); the Joint Committee on Solar Terrestrial Relationships; and the Inter Union Commissions on Radio-Meteorology (IUCRM), Applied Radioactivity, and an Ad hoc Committee on Problems of Geochemistry. Liaisons were appointed to UNESCO, the UN Cartographic Office, WMO, PAIGH, and the Pacific Science Association (PSA). A liaison to the Pan Indian Ocean Science Association (PIOSA) was discontinued following this Assembly.

Forty Union resolutions were passed (IUGG Archives, 1963). They included support for the World Magnetic Survey, the International Years of the Quiet Sun, the Upper Mantle Project, and expedited transmission of geophysical data to the World Data Centers; requests that ICSU approach ITU to arrange for an allocation of frequencies for electro-magnetic distance measurements; that an existing regional warning system for tsunamis be regarded as the nucleus of an International Tsunami Warning System; that improved heat flow measurements be taken; that more aeromagnetic surveys be done and improved ground-based magnetic measurements be made; that a joint Panel of Experts on Oceanographic Tables and Standards be supported; that UNESCO should call upon IUGG to serve as the scientific advisor of the International Hydrological Decade; and that a Permanent Service on the Fluctuation of Glaciers be formed.

4.2 XIV General Assembly (25 September–7 October 1967, Zurich, Switzerland)

IUGG President Joseph Kaplan (USA) presided. Other members of the Bureau were Vice Presidents Keith E. Bullen (Australia) and Jean Coulomb (France), Secretary General George Garland (Canada), Treasurer Einar Andersen (Denmark), and members Bert Bolin (Sweden) and Valery Troitskaya (USSR). The invitation from the Swiss Academy of Sciences (Schweizerische Akademie der Naturwissenschaften) to host the General Assembly was not received until 1965. To accommodate the Assembly, meetings of Council and Plenary Sessions were held in Zurich and Association programs were distributed across Zurich (the International Association of Volcanology (IAV), IASPEI), Bern (IASH, IAPO), St. Gall (IAGA), and Lucerne (IAG, IAMAP). Fritz Kobold was Chair of the Swiss Local Organizing Committee; the green–blue–white logo representing the Earth, the ocean, and the atmosphere that IUGG uses today originated with the Swiss local organizing committee for this Assembly (Fig. 3). Once again, no venue for the 1971 General Assembly was apparent, and the matter was left to the incoming officers.

During the quadrennium, ICSU created the Committee on Water Research (COWAR) to promote contacts between the Unions dealing with water issues. IUGG became instrumental in the Upper Mantle Project. The Union Committee on Problems of Geochemistry was (temporarily) disbanded and absorbed into the newly renamed International Association on Volcanology and Chemistry of the Earth's Interior (IAV became IAVCEI). IAPO also changed their name to IAPSO ("Physical Sciences of the Ocean" instead of "Physical Oceanography").

Twenty-five Union resolutions were passed (IUGG Archives, 1967). They urged establishment and continuation of geophysical observatories for water resources, heat flow, seismology, volcanology (especially in Iceland and Italy), and geomagnetism; support of the Upper Mantle Project, the International Active Sun Years, the International Geological Correlation Programme (IGCP), an inter-agency Working Group on Statistical Data on Wind and Waves (already concerned with maritime pollution), the Geodetic Reference System 1967, and development of a world volcanology map. The assembly approved the charter for the Central Bureau

Figure 3. Elena Lyubomova (USSR delegate) at the General Assembly in Zurich. Note the badge with the IUGG logo used for the first time (photo: courtesy of Seiya Uyeda).

for Satellite Geodesy and IUGG's participation in the Global Atmospheric Research Programme.

4.3 XV General Assembly (2–14 August 1971, Moscow, USSR)

IUGG President Jean Coulomb (France) presided. Other members of the Bureau were Vice Presidents Hisashi Kuno (Japan, 1967–1969) and Liviu Constantinescu (Romania, 1969–1971), Secretary General George Garland, Treasurer Einar Andersen (Denmark), and members Liviu Constantinescu (Romania, 1967–1969), Thomas Malone (USA), and Alexei Oboukhov (USSR). The President of the Soviet Organizing Committee was Alexandar P. Vinogradov; the Opening Ceremony was held in Kremlin Congress Hall (Fig. 4) and scientific meetings were at the Moscow State University. It was noted that delegates from the People's Republic of China were unable to get visas to attend the assembly because of the Sino-Soviet ideological split between the Communist parties of PRC and of USSR and ongoing border military conflict.

In response to growing concerns about the detrimental effects of human populations, ICSU established the Scientific Committee on Problems of the Environment (SCOPE) in 1969. IUGG/IUGS began to develop an Inter-Union Commission on Geodynamics. Reports were received from the Tsunami Commission and the Upper Mantle Committee.

Figure 4. XV General Assembly in Moscow, USSR. **(a)** Opening ceremony and **(b)** delegates attending the ceremony in the Kremlin Congress Palace Hall (photos **a** and **b**: courtesy of Alik Ismail-Zadeh). **(c)** The USSR produced a stamp on the occasion of the IUGG General Assembly (photo: https://commons.wikimedia.org/wiki/File:The_Soviet_Union_1971_CPA_4005_stamp_(Satellite_over_Globe).jpg, last access: 30 January 2019).

The Union established a Working Group on Advice to Developing Countries, to coordinate with the ICSU Committee on Science and Technology in Developing Countries (COSTED). A new Union Committee on Geochemistry found support. Because considerable progress had been made in the understanding of hydrological processes, IASH became IAHS ("Hydrological Sciences" instead of "Scientific Hydrology"); its Statutes and By-laws were revised and its scientific structure was reorganized. The inter-Association Committee on Mathematical Geophysics (CMG) was established at this General Assembly. It originated with the former Upper Mantle Committee's Working Group on Geophysical Theory and Computers. The CMG, under the leadership of Vladimir I. Keilis-Borok, continued to organize symposia such as the eight annual symposia on geophysical theory and computer applications that had been held from 1964 through 1971.

Twenty-one Union resolutions were passed (IUGG Archives, 1971). They supported adoption of the International Gravity Standardization Net 1971 (correcting a 1909 datum), and continuations of the work begun by the International Magnetospheric Study and the Global Atmospheric Research Programme, and approval of an international and inter-Union study group under the auspices of IAG to strengthen cooperation on lunar laser ranging experiments and theory. Several resolutions emphasized the need for new geophysical measurements such as for ozone (both with ground-based and satellite instruments), boundary-layer phenomena (oceanic and atmospheric), high-altitude (about 50 km) wind and air temperatures, lunar and tidal effects on the magnetosphere, the solar constant, the optical properties of aerosols and clouds, active and dormant volcanoes to study the potential benefits of geothermal energy, tide gauge measurements (mean sea level), and the absolute density and conductivity of seawater. Resolution 20 sought an understanding of Planet Earth and supported a United Nations Conference on the Human Environment (June 1972) and declaration of a special Environmental Period to "start the process of bringing together the environment and man into a harmonious state."

4.4 XVI General Assembly (25 August–6 September 1975, Grenoble, France)

IUGG President Henry Charnock (UK) presided. Other members of the Bureau were Vice President Attia Ashour (Egypt); Secretary General George Garland (Canada, until 1973) and Adjoint Secretary General Paul Melchior (Belgium, 1971–1975), Treasurer Elvin Kejlso (Denmark), and members William Ackermann (USA), Liviu Constantinescu (Romania), and Nikolai Shebalin (USSR). The Assembly was held on the campus of the University at Saint Martin D'Hères and hosted by the French National Committee for Geodesy and Geophysics (of the French Academy of Sciences), chaired by Georges Laclavère. Participants included guests from UNESCO, WMO, and the International Atomic Energy Agency (IAEA). There were Union Lectures, and more than thousand papers were presented. There were reports from the Inter-Union Commission on Geodynamics; the inter-Association Committee for Advice to Developing Countries, CMG, the Tsunami Committee and the Commission on Geochemistry. A Joint IASPEI-IAGA Inter-Association Commission on Planetary Sciences was initiated.

Twenty Union resolutions were passed (IUGG Archives, 1975). They included the adoption of ICSU Resolution 8 concerning the right to free movement of scientists, and expressions of support for the World Data Centers and the Middle Atmosphere Program. The Union noted concern that human activities might be producing changes in stratospheric composition and recommended that nations monitor and evaluate long-term trends. Several resolutions addressed adoption of uniform values (the speed of electromagnetic radiation in vacuo) and terminology, including use of SI units in geodesy and geophysics and standard legends in hydrological maps. Recommendations included changes in the constitution of the IUCRM and inclusion of radio oceanography, and a volcanology research center in the Pacific. The Union supported the work of the IAHS International Commission for Snow and Ice to produce a World Inventory of Perennial Snow and Ice Masses, the need for a better determination of the solar constant, improved polar motion measurements using Doppler satellite tracking, and low-altitude satellite magnetic survey data.

4.5 Meeting of the Council and Extraordinary General Assembly (6 August 1977; Durham, UK)

IUGG President Attia Ashour (Egypt) presided. Other members of the Bureau were Vice President George Garland (Canada), Secretary General Paul Melchior (Belgium), Treasurer Elvin Kejlso (Denmark), and members Nicolai Shebalin (USSR), Henri Lacombe (France), and Carl Kisslinger (USA). Forty-six Member countries were represented, and nine countries voted by correspondence on a three-part motion to admit the People's Republic of China (PRC) into membership. The motion passed by a vote of 47 to 7 with 1 abstained. The motion also indicated that "the representation assumed until now by the Taiwan delegation must be cancelled". This was because the IUGG Statutes did not permit more than one Adhering Body per member country.

To briefly describe the circumstances that led up to the Extraordinary General Assembly (EGA), the Republic of China (ROC) became a constitutional entity in 1912, but national and international conflicts resulted in a division in 1949 such that most of the land mass became part of the PRC, based in Beijing. There had been discussions as early at 1956 that the PRC should be invited to apply for membership in IUGG (they were a participating country in the IGY). However, it was the ROC that first submitted an application in 1957 and after much discussion, the ROC was admitted at the IUGG General Assembly in Zurich (1967). In 1971, the United Nations expelled the ROC as a member, accepting instead the PRC. Several other nations followed suit and cancelled diplomatic recognition of the ROC. In 1974, the PRC formally refused to participate in ICSU programs because the ROC had not been expelled from ICSU membership.

Because Australia did not recognize the ROC, no visas could be issued to any Taiwanese visiting scientists at the IUGG General Assembly in Canberra (1979) "other than in a private capacity". In addition, in 1976 the International Union of Geological Sciences had voted to cancel the IUGS membership of the Republic of China, and approved an application for membership by the People's Republic of China. So it is no surprise that IUGG took the measures they did – but the story does not end there.

ICSU had long upheld non-discriminatory policies with regard to the rights of scientists. An ICSU resolution passed in 1958 affirmed the right to participate in scientific activities "without regard to race, religion or political philosophy." A resolution on the Free Circulation of Scientists passed in 1963 asked that its member Unions, with regard to all scientific meetings, "ensure the fundamental right of participation, without any political discrimination". This policy was reaffirmed in 1966 and 1972 and was incorporated in the ICSU Statutes in 1972. At the ICSU Assembly in Washington D.C., USA (1976), a resolution on the Principle of Universality was passed which expressed "eagerness" to welcome the scientific community of the People's Republic of China while recommending that Unions provide for adherence by scientific communities through an appropriate scientific institution "provided they can be listed under a name that will avoid misunderstanding about the territory represented."

In 1982, the 19th General Assembly of ICSU (Cambridge, UK) admitted the China Association for Science and Technology (CAST) while affirming that the "Academy located in Taipei, China, shall retain its present membership in ICSU", and urged amendment to Union Statutes that would "promote the universality of science." In 1995, the IUGG Council changed Statutes 4 and 5 so that "under extraordinary circumstances, the Council of IUGG ... may admit a suitably designated additional Adhering Body for a country." Consequently, "the Academy of Sciences located in Taipei, China" was admitted as a member in Category IV, and remains a member today.

4.6 XVII General Assembly (3–15 December 1979, Canberra, Australia)

IUGG President Attia Ashour (Egypt) presided, and the members of the Bureau were the same as for the 1977 Extraordinary General Assembly. The Australian Academy of Sciences hosted the Assembly; Peter V. Angus-Leppan was Chair of the Organizing Committee and Bruce P. Lambert was Executive Director. This was the first General Assembly of the Union in the Southern Hemisphere, and was held on the campus of the Australian National University. Sir Zelman Cowen, Governor-General of Australia, addressed the Opening Ceremony. The program featured Union Lectures, inter-Association symposia, and scientific committee meetings.

IUGG Committees on Advice to Developing Countries, Mathematical Geophysics, and Geochemistry were active during the quadrennium, plus one on a "Standard Earth Model." A report from a task group that began in 1977 examining whether to present a joint IUGS/IUGG program to ICSU to study the lithosphere was approved. Termination of the Inter-Union Commission on Geodynamics was extended to 1980. The purview of the IUCRM (Radio-Meteorology) was expanded to include Radio-Oceanography. Apropos to the business of the EGA in 1977, the delegates were asked if they were in favor of an ICSU proposal to replace the word "country" with "territory" in the Statutes, which would then permit both the ROC and the PRC to be members. The vote failed.

Seventeen Union resolutions were passed (IUGG Chronicles, 1980). The resolutions supported the (now Abdus Salam) International Center for Theoretical Physics in Trieste, Italy; the Alpine Experiment within GARP/WCRP; the International Polar Motion Service; financial aid by FAGS to the Service for Mean Sea Level; and an IAU resolution that the IAU Working Group on the Determination of the Rotation of the Earth be reconstituted to be joined with IUGG. The Union recommended that Geodetic Reference System 1980 replace an earlier version; that the IAU reconsider its choice of a nutation series to determine Earth orientation parameters; that ICSU encourage UNESCO to establish a Natural Hazards Unit; and again urged that a center for volcanology research be established in the Pacific. The Union endorsed continued development and application of space methods for geodetic observations and requested that COSPAR formally include the IAG Commission on International Coordination of Space Techniques for Geodesy and Geodynamics within its structure. The Union acknowledged the contributions of the U.S. Navy Navigation Satellite System to geodetic studies. IUGG also passed several resolutions of instruction to itself. These included asking its member countries to balance support of basic research in the geosciences with practical applications, and to establish National Committees and Correspondents to the Associations; publishing a list every 2 years of international scientific programs sponsored entirely or in part by IUGG and its Associations; inviting the incoming Bureau to make changes in the Statutes to permit admission of adhering bodies "necessary for the complete representation of the geodesists and geophysicists of any country"; and planning the scientific program at General Assemblies such that both interdisciplinary symposia and understandable Union lectures and Association symposia in their own specific fields are presented.

4.7 XVIII General Assembly (15–27 August 1983, Hamburg, Federal Republic of Germany)

IUGG President George D. Garland (Canada) presided. Other members of the Bureau were Vice President Nikolai Shebalin (USSR), Secretary General Paul Melchior (Belgium), Treasurer Ole Bedsted Andersen (Denmark), and members James Dooge (Ireland), Henri Lacombe (France), and Carl Kisslinger (USA). The German National Committee for Geodesy and Geophysics hosted the Assembly, which was chaired by Wolfgang Torge. There were greetings from Karl Carstens, President of the Federal Republic of Germany, and Heinz Riesenhuber, Federal Minister of Research and Technology. The Federal Republic of Germany produced the stamp (Fig. 5) on the occasion of the IUGG General Assembly in Hamburg in 1983.

Figure 5. Stamp celebrating the XVIII IUGG General Assembly in Hamburg in 1983 (photo: https://commons.wikimedia.org/wiki/File:DBP_1983_1187_GeodC3A4sie_und_Geophysik.jpg, last access: 30 January 2019).

Twenty-one inter-disciplinary symposia were organized, including one on the ocean and CO_2 climate response. For the first time, the number of participants adhering to each Association was recorded. Each Association had convened their own scientific assembly between Union Assemblies and it was agreed that the Associations could arrange their own programs within a GA. The Union Committee on Geochemistry was disbanded and the Committee for Advice to Developing Countries was restructured. IUGG named a liaison to the International Hydrographic Organization.

Union resolutions (IUGG Archives, 1983) supported Project MERIT (Measurements of Earth's Rotation and Inter comparison Techniques) and requested WMO support to collect global wind and pressure data; the WCRP's request for meteorological and oceanic data in the North Pacific (i.e., ships-of-opportunity); an ICSU resolution requesting an assessment of the biological and physical effects of the use of nuclear weapons; the need for transportable apparatus for highly accurate absolute gravity measurements; and invited participation in the IUGS/IASPEI Commission on the Geological Map of the World and in the IUGG/IUGS Inter-Union Commission on the Lithosphere. IUGG recommended satellite observations of the middle atmosphere to reliably predict the effects of human activities; MST/ST radars and lidars near equatorial latitudes to study the equatorial middle atmosphere; and links between international aviation organizations and IAVCEI with regard to aircraft and volcanic ash plumes. IUGG urged national support for training seminars for the African Doppler Survey; information necessary to obtain navigational positions from the new USA and USSR satellite systems; high-latitude orbiting satellites to record surface elevations of the Antarctic and Greenland ice sheets; support for UNESCO's Regional Office for Science and Technology for Southeast Asia (ROSTSEA) to establish a center for volcanological studies; participation in several ICSU programs on solar–terrestrial interactions; calibrated radiation energy exchange observations in data-poor regions for studies of climate systems; and that compilations of climate data be made available in convenient format at concessional rates especially to scientists in developing countries.

4.8 XIX General Assembly (9–22 August 1987, Vancouver, Canada)

IUGG President Devendra Lal (India) presided. Other members of the Bureau were Vice President Carl Kisslinger (USA), Secretary General Paul Melchior (Belgium), Treasurer Ole Bedsted Andersen (Denmark), and members James Dooge (Ireland), Vladimir Keilis-Borok (USSR), and Helmut Moritz (Austria). The Canadian National Research Council (Larkin Kerwin, President) and the University of British Colombia (David W. Strangway, President) were the primary co-hosts for the Assembly. The Chair of the Canadian National Committee for Geodesy and Geophysics was Gordon A. McBean. The Assembly took place on the campus of the University of British Columbia. AGU agreed to publish 10 IUGG volumes in its Geophysical Monograph series based on the presentations by Union Lecturers and selected talks at 20 inter-Association symposia (see Appendix B). Poster sessions were encouraged at the Assembly. In his opening address, President Lal referenced the observed depletion of ozone in the Antarctic and dramatic changes in atmospheric CO_2 and temperature.

The Union Committee on the Study of the Earth's Deep Interior (SEDI) was established in 1987 to cut across the traditional discipline-oriented bounds of the Associations (especially IAG, IAGA, IASPEI, and IAVCEI) to develop a coherent and consistent picture of the workings of the Earth's interior. The only other two Union Committees reporting were the CMG and the Committee for Advice to Developing Countries. In cooperation with the IAU, IUGG established in 1988 the International Earth Rotation Service (IERS). Numerous inter-Union relationships continued and there was a plea to extend the termination date of the International Program on the Lithosphere. A workshop was proposed to consider the possible contributions of IUGG to the International Geosphere-Biosphere Programme (IGBP), a new ICSU interdisciplinary program. The generous support of UNESCO to the Associations was acknowledged. SCOPE published a seminal report, "The greenhouse effect, climatic change and ecosystems", which summarized the scientific findings of a 1985 conference on the "Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts" co-sponsored by ICSU, WMO, and the United Nations Environmental Program (UNEP). This was the first comprehensive international assessment of the environmental impact of atmospheric greenhouse gases.

Nine resolutions were passed (IUGG Archives, 1987). They supported decisions by URSI and IAU to approve the Bureau International des Poids et Mesures (BIPM) as the authority for International Atomic Time; the establishment of the International Decade for Natural Hazard Reduction for the period 1990 to 2000; and IGBP activities. IUGG recommended installation of new and recalibrated tide gauges to include telemetered measurements of atmospheric pressure and geodetic position; and the launch of a dedicated satellite gravity mission by the mid-1990s. IUGG urged modernization of ICSU data management systems; and reconsideration by countries planning to close down long-standing geophysical observatories and stations.

4.9 XX General Assembly (11–24 August 1991, Vienna, Austria)

IUGG President Vladimir I. Keilis-Borok (USSR) presided. Other members of the Bureau were Vice President Carl Kisslinger (USA), Secretary General Paul Melchior (Belgium), Treasurer Soren Gregersen (Denmark), and members Gordon McBean (Canada), Helmut Moritz (Austria), and Ye Duzheng (China). This was Paul Melchior's last General Assembly; he had served as IUGG Secretary General and Adjoint Secretary General for 20 years. The Austrian National Committee of Geodesy and Geophysics hosted the Assembly at the Technical University of Vienna. Hans Sünkel was the Chair of the local organizing committee. Maria Fekter, Secretary of State and Minister of Economic Affairs addressed the Opening Ceremony. AGU continued to publish the Union Lectures and Symposia as IUGG volumes in its Geophysical Monograph series, and eight volumes were published during 1992–1994 (see Appendix B).

During this GA, a political upheaval occurred in the USSR that was of great concern to the delegates at the Assembly from that country, some of whom feared they could not go home. It would be remiss not to include this memory of the General Assembly and the personal impact it had on all of the delegates. While the worst outcome did not happen then, ultimately, the ramifications of this event changed the very structure of IUGG. The USSR delegates left their country for Vienna to attend the IUGG General Assembly, and returned to their country in political chaos, which would disintegrate in a few months into 15 independent states. In 1992, Russia replaced the USSR as a member of IUGG, and four other countries of the former Soviet Union joined the Union later: Armenia, Azerbaijan, Estonia, and Georgia.

Another geopolitical situation influenced this quadrennium. IUGG adherence to ICSU resolution on the Free Circulation of Scientists caused the joint scientific assemblies of IAGA and IASPEI in 1989, originally planned in Oslo, Norway, to be relocated because the Government of Norway, in protest to the conditions of apartheid then present in South Africa, decided in 1987 not to issue visas to South African applicants. Neither could the University of Oslo permit entrance into University facilities, including meeting rooms, of South African nationals. As a result, the joint IAGA/IASPEI assembly in Oslo was cancelled. In 1989, IAGA met in Exeter, UK, and IASPEI met in Istanbul, Turkey.

Besides the usual Union symposia and Association scientific talks and poster sessions, there was continued general discussion of how to improve the capacity for science in developing countries. It was decided that the Associations could best provide support, and the IUGG Committee on Advice to Developing Countries was discontinued (however, it was reinstated at the 1995 GA). The ILP continued as an inter-Union (IUGG/IUGS) body. Under the leadership of IAG, the first International Terrestrial Reference Frame (ITRF) was released in 1988.

Union resolutions (IUGG Archives, 1991) supported an IAU resolution defining the Conventional Terrestrial Reference System and further specified system requirements; and the installation and operation of ocean-bottom observing systems that use submarine cables abandoned by telephone companies. IUGG recommended a major campaign for high time resolution measurement of Earth rotation by space techniques to be coordinated with the International Earth Rotation Service (IERS); implementation of a dedicated mission (ARISTOTELES) for the improved determination of the Earth's gravity and magnetic fields; the concept of an International GPS Geodynamic Service (IGS), and that existing global geodetic systems be used to carry out intensive observing campaigns; development of additional knowledge needed to reduce the disastrous effects of extreme natural events. IUGG urged that organizations, agencies, and Member countries optimize and possibly co-locate the geographical distribution of stations that make continuous Earth and space observations.

4.10 XXI General Assembly (2–14 July 1995, Boulder, Colorado, USA)

IUGG President Helmut Moritz (Austria) presided. Other members of the Bureau were Vice President Peter Wyllie (USA), Secretary General Georges Balmino (France), Treasurer Søren Gregersen (Denmark), and members Gordon McBean (Canada), Ye Duzheng (China), and Andrei Monin (Russa). The theme of the General Assembly was "Geophysics and the Environment", and IUGG celebrated its 75th anniversary looking forward to the challenges for the next 25 years. The US National Committee for Geodesy and Geophysics, under the National Academy of Sciences, was the host, and AGU served as the local organizing committee. Chris Harrison was the Chair of the US National Committee, and David S. Chapman acted as Chair of the Local Organizing Committee. Carl Kisslinger led the Colorado Host Committee. The International Association for the Physical Sciences of the Oceans did not attend this Assembly. However, Chris Mooers organized several inter-disciplinary symposia that offered an oceans sciences component to the program.

At this GA, IAMAP was renamed IAMAS ("Sciences" instead of "Physics"). IUGG discontinued a formal link with the Pacific Science Association and reinstated the Committee for Developing Countries. IUGG formed the Committee for the Problems of the International Decade for National Disaster Reduction (IDNDR) as a Union response to IDNDR, established by the decision of the UN General Assembly in 1991; this Commission evolved into the Commission on Geophysical Risk and Sustainability in 2000. IAG established the International Service for Geodynamics (IGS) in 1994 after a successful pilot program of more than a year. IGS provides the status (including orbits) for all GPS satellites as well as other positioning data and products.

Union resolutions (IUGG Archives, 1995) recommended that national agencies and institutions contribute to the operation of the International Earth Rotation Service; the implementation of a dedicated satellite gravity mission; and that IAU work with IUGG to define of a timescale including a convention for the continuous counting of days adapted to the archival and exchange of time-dependent data used in analysis of astronomical as well as geodetic and geophysical phenomena. IUGG urged support of research programs aimed at the design, deployment, and operation of ocean-bottom magnetic observatories.

4.11 XXII General Assembly (19–30 July 1999, Birmingham, UK)

President Peter J. Wyllie (USA) presided. Other members of the Bureau were Vice President Uri Shamir (Israel), Secretary General Georges Balmino (France), Treasurer Søren Gregersen (Denmark), and members Jianyun Chen (China), Andrei S. Monin (Russia), and Seiya Uyeda (Japan). Graham Westbrook chaired the Local Organizing Committee, and Kathryn Whaler chaired the Scientific Programme Committee. Held on the campus of the University of Birmingham, the informal theme was "Geoscience in the Service of Society." Seven Union Symposia, 48 Joint Symposia, and four Union Lectures were presented. The topic of climate change was discussed widely.

The Union Megacities Task Force, and the Alliance for Capacity Transfer were initiated. The Committee for Developing Countries, reinstated in 1995, was again disbanded and funds were allocated for inter-Association initiative grants to benefit developing countries. Reports were received from the ILP, CMG, SEDI, and the Inter-Association Tsunami Committee; all had held successful meetings. Uri Shamir attended as the IUGG representative to the UNESCO/ICSU World Conference on Science in Budapest in June 1999. IAPSO further modified their name by adding an "s" to Ocean to become the "International Association for the Physical Sciences of the Oceans."

Union resolutions (IUGG Archives, 1999) supported the Integrated Global Earth Monitoring Systems (IGEMS) and the free and unrestricted transfer of data; studies of the prevention and mitigation of natural disasters in continuation of the IDNDR program beyond the decade including the problems of megacities; the International Human Dimensions Program (IHDP), WCRP, and IGBP. The Union recommended that ITU should not make changes to the existing allocations of the radio frequencies for Global Navigation Satellite Systems; and that open, free, and un-delayed access to all raw and processed waveform data be made available from the International Monitoring System (IMS) for the Comprehensive Test Ban Treaty (CTBT) to seismological data centers.

5 Distinguished leadership

This section highlights those extraordinary scientists and science administrators who led the Union and significantly contributed to IUGG development after WWII until the end of the 20th century.

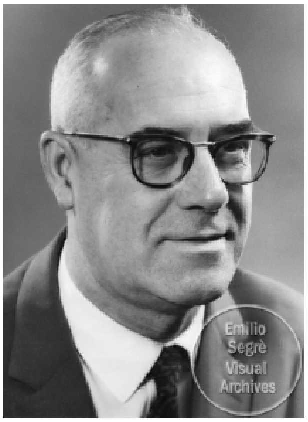
Bjørn Helland-Hansen, President (1946–1948): Bjørn Helland-Hansen (Norway, 1877–1957) was an oceanographer. He studied the variation patterns of the weather in the northern Atlantic Ocean and of the atmosphere. He graduated from the University of Christiania (now University of Oslo). He became Professor of Oceanography at the Bergen Museum in 1915, and Director of the Geophysical Institute, University of Bergen in 1917. Helland-Hansen was President of IAPSO from 1936 to 1946 before he was elected IUGG President. He was a member of the Prussian Academy of Sciences and a member of the Member of the Academy of Sciences of the German Democratic Republic. An island in the Russian Arctic, east of the Geiberg Islands, was named "Gellanda-Gansena" after Helland-Hansen. (Courtesy of Ukjent/NTB).

James Martin Stagg, Secretary General (1946–1951): James M. Stagg (UK, 1900–1975) was active in IATME, the predecessor to IAGA. He was leader of the British Polar Year Expedition to Arctic Canada, 1932–1933, and received his PhD from Edinburgh University in 1936. He was Superintendent of the Kew Observatory in 1939. He was Chief Meteorological Officer for the Supreme Command, Allied Forces, Europe 1943–1945, and was Director of Services for the Meteorological Office in 1944–1946. As IUGG Secretary General, he was instrumental in the post-war reconstruction leading to the Eighth General Assembly in Oslo in 1948, ensuring the continuation of IUGG and restarting its development. He was elected as president of the Royal Meteorological Society in 1959. At the time of his death he was President of the IUGG Finance Committee, having served on the Committee since 1967. (Source: IUGG archives)

Felix A. Vening-Meinesz, President (1948–1951): Felix Andries Vening-Meinesz (the Netherlands, 1887–1966) was a geodesist and geophysicist. One of the leading geoscientists of the first half of the 20th century, he began his career making gravity measurements at sea in order to determine the shape of the geoid. Discoveries of anomalies in the gravity field led him to develop new theories about the mechanics of the Earth's crust and mantle and continental drift. He was a professor of geophysics and geodesy at the universities of Utrecht and Delft, and was the Director of the Royal

Dutch Meteorological Institute (KNMI). He served as IAG President from 1933 to 1945. He was a Member of the Royal Netherlands Academy of Arts and Sciences, and Fellow of the Royal Society. A gravimeter and a mathematical function used in geodesy, and a crater on the Moon, are named after Vening-Meinesz. The European Geoscience Union's Geodesy Division established the Medal in recognition of the scientific achievements of Vening-Meinesz. (Courtesy of AIP Emilio Segrè Visual Archives)

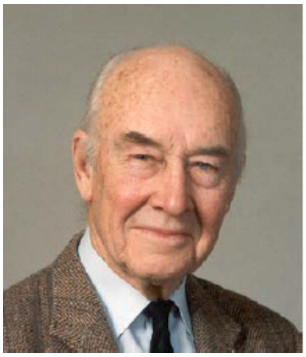
Sydney Chapman, President (1951–1954): Sydney Chapman (UK, 1888–1970) was a geophysicist and mathematician, and graduated from the University of Manchester and Trinity College Cambridge. Chapman is recognized as one of the pioneers of solar–terrestrial physics. In 1946, Chapman coined the term "aeronomy", which is used today to describe the scientific field of high-altitude research into atmosphere–space interaction. During his distinguished career he was affiliated with the universities of Cambridge, Manchester, London, Oxford, Alaska, and Colorado. Chapman was also IAMAS President (1936–1948) and IAGA President (1948–1951). He served as Chair of the Special Committee for the IGY (1953–1958). He was elected fellow of several national academies, including the Royal Society and US National Academy of Sciences. Lunar crater Chapman is named in his honor. AGU organizes "Chapman Conferences", and the Royal Astronomical Society established the Chapman Medal in his memory. (Source: IUGG archives)



Georges R. Laclavère, Secretary General (1951–1963): Colonel Georges R. Laclavère (France, 1906–1994) was Chief Editor of the IUGG Chronicle from 1957 to 1990. He also served for many years as the FAGS Secretary. His early career was in surveying and geodetic work in France and Morocco, becoming Ingenieur Géographique for the Institut Géographique National (IGN) in Paris, France, in 1940. He became Director General of the IGN in 1963 and was instrumental in bringing IGN into the space age. He was a member of the Special Committee for the IGY (1956–1957), the first elected President of the ICSU Scientific Committee on Antarctic Research (1958–1963), and was a Bureau member and Treasurer of ICSU (1959–1965). (Courtesy of AIP Emilio Segrè Visual Archives)

Kalpathi R. Ramanathan, President (1954–1957): Kalpathi Ramakrishna Ramanathan (India, 1893–1984) was a physicist and meteorologist. He started his research career with Nobel Laureate Chandrasekhara V. Raman with their pioneering paper on the X-ray diffraction of liquids (1923). He was known for his discovery work on ozone and airglow, and contributed actively in the areas of ionospheric physics, space physics, geomagnetism and radio astronomy. He became the Founder-Director of the Physical Research Laboratory at Ahmedabad in 1947, after his retirement from the India Meteorological Department. He served as IAMAS

President from 1951 to 1954. He was a Fellow of the Indian Academy of Sciences and an Honorary Fellow of the Royal Meteorological Society of London. The Indian National Science Academy established the Kalpathi Ramakrishna Ramanathan Medal in 1987 in honor of him. (Courtesy of Creative Commons BY-SA 4.0)

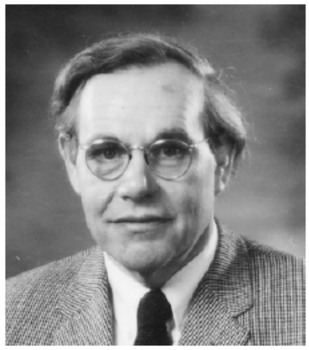


John Tuzo Wilson, President (1957–1960): John Tuzo Wilson (Canada, 1908–1993) was a geophysicist and geologist who achieved worldwide acclaim for his contributions to the theory of plate tectonics. He graduated from Trinity College at the University of Toronto in 1930, and obtained his PhD in geology in 1936 from Princeton University. After completing his studies, Wilson enlisted in the Canadian Army and served in World War II; he retired from the army with the rank of Colonel. He was the Principal of Erindale College at the University of Toronto, and the Director General of the Ontario Science Centre. J. Tuzo Wilson served IUGG as Chair of Finance Committee (1948–1954) and Vice President (1954–1957). He was a Fellow of the Royal Society of Canada, of the Royal Society of London and of the Royal Society of Edinburgh. He was AGU President. The John Tuzo Wilson Medal of the Canadian Geophysical Union recognizes achievements in geophysics. His name was given to two young Canadian submarine volcanoes called the Tuzo Wilson Seamounts. The Wilson cycle of seabed expansion and contraction bears his name. (Courtesy of Creative Commons BY-SA 3.0)

Vladimir V. Beloussov, President (1960–1963): Vladimir Vladimirovich Beloussov (USSR, 1907–1990) was a geoscientist, and a prominent advocate of alternatives to the theories of plate tectonics and seafloor spreading during the period of the 20th century in which debate on these subjects was most intense. Beloussov graduated from the Lomonosov Moscow State University and Leningrad State University, and received his PhD in 1938 from the USSR Academy of Sciences. He was head of the Geodynamics Department of the Smidt Institute of the Physics of the Earth of the USSR Academy of Sciences in Moscow. and Professor at the Moscow Geological Surveyance Institute (1943–1949) and the Lomonosov Moscow State University (1953–1990). During the 1960s he led three expeditions to the East African Rift to study continental structure and the Earth's mantle. Beloussov served as Member of the Special Committee for the IGY from 1954 to 1958 and was IUGG Vice President (1957–1960). He was an initiator and Chair of the IUGG Upper Mantle Project (1964–1970). He was elected to the USSR Academy of Sciences and several national academies. (Courtesy of the Russian Academy of Sciences)

Joseph Kaplan, President (1963–1967): Joseph Kaplan (USA, 1902–1991) was a chemist and atmospheric scientist. He graduated from the Baltimore Polytechnic Institute (1921), earned a bachelor's degree in chemistry (1924), and a doctorate in physics (1927) from Johns Hopkins University. His research, largely concerned with the spectra of diatomic molecules and, more specifically, in afterglows of nitrogen and oxygen and their mixtures, began at Princeton University. In 1928, he accepted an assistant professorship at the University of California at Los Angeles (UCLA), becoming an associate professor in 1935 and a full professor in 1940. He was appointed chairman of the Department of Physics (1939–1944) and director of the Institute of Geophysics (1946–1947). Kaplan became chairman of the U.S. National Committee for the IGY (1953–1963). He served IUGG as Vice President (1960–1963), and was an Ordinary Member of the ICSU Executive Board (1962–1967). He was elected to membership in the US National Academy of Sciences (1957) as well as numerous other scientific societies. (Courtesy of the National Academies Press)

Jean Coulomb, President (1967–1971): Jean Coulomb (France, 1904–1999) was a geophysicist and mathematician, and his work was in the fields of seismology (theory of surface waves), geomagnetism, and meteorology (atmospheric electricity and the physics of clouds). He was a professor in the Faculty of Sciences of the University of Paris (1941–1972) and Director of the Institut de Physique du Globe de Paris (1941–1959). He was Director-General of the French National Centre for Scientific Research (CNRS, 1957–1962), President of the French National Centre for Space Studies (CNES, 1962–1967), President of the Bureau des Longitudes (1967–1969), and ICSU President (1972–1974). In 1960, he was elected to the French Academy of Sciences, and served as its President (1976–1977). (Courtesy of Creative Commons BY-SA 4.0)



Henry Charnock, President (1971–1975): Henry Charnock (UK, 1920–1997) was a marine meteorologist. He earned his MSc and PhD in meteorology at Imperial College of London. He started his career in the UK National Institute of Oceanography (NIO), accepted a Chair in Physical Oceanography at the University of Southampton in 1966, but returned to the NIO in 1971 as Director. Shortly thereafter, several small laboratories were combined to form the Institute of Oceanographic Sciences with Charnock as Director. He took on the presidency of IUGG to replace the Australian meteorologist Charles H. B. Priestley, who had been formally elected as president but had declined at short notice. He returned to Southampton in 1978 and became Head of the Department in 1979, later Deputy Vice Chancellor of the University (1982–1984). He was SCOR Vice President (1980–1982) and President of the Royal Meteorological Society (1982–1984). He was Fellow of the Royal Society. (Courtesy of the Royal Society)

Baron Paul Melchior, Secretary General (1973–1991): Baron Paul Melchior (Belgium, 1926–2004) graduated from the Free University of Brussels. From 1949 he worked at the Royal Observatory of Belgium in Uccle. His major contributions were in the field of geodynamics, studies of the Earth's rotation and tidal deformations. Among his many duties, he was Director of the Royal Observatory of Belgium from 1981 till 1990, Director of the International Center of Earth Tides from 1958 till 1995 and Professor at the Université Catholique de Louvain from 1972 till 1990. Melchior was elected AGU Fellow, Honorary Fellow of the Royal Astronomical Society, and foreign Member of the Finnish, Spanish, The Netherlands, and Romanian academies of sciences. The IUGG Bureau bestowed a title of Honorary Secretary General to Baron Paul Melchior for his outstanding service to IUGG. (Courtesy of the Royal Observatory of Belgium)

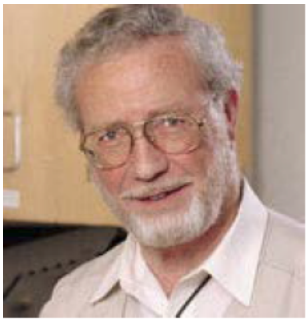
Attia Ashour, President (1975–1979): Attia Abdel Salam Ashour (Egypt, 1924–2017) was a physicist and mathematician. His work was in the field of theoretical geomagnetism and other physical and mathematical fields. He obtained his BSc in Mathematics (1944), PhD (1948), and DSc (1967). He started his teaching career in the Mathematics Department, University of Cairo (UoC), Egypt, and became professor of UoC in 1948, Head of the Mathematics Department for about 15 years before his retirement in 1984. Ashour was visiting professor in France, Germany, Italy, Nigeria, and UK. He served IUGG as Vice President (1975–1979), and Member (1983–1995) and Chair (1995–1999) of Finance Committee. He was fellow and Vice President of the African Academy of Sciences, and President of the International Centre of Pure and Applied Mathematics in Nice, France (1992–1996). He was a Member of the Advisory Board to the Director General of UNESCO on "Science and the 21st Century". Ashour was an IUGG Fellow and elected fellow of several national societies and academies. (Source: IUGG archives)

George Garland, President (1979–1983) and Secretary General (1963–1973): George D. Garland (Canada, 1926–2008) was professor of the Department of Physics, University of Toronto, Toronto, Canada. Garland obtained his B.A. in 1947 from the University of Toronto and PhD in 1951 from St. Louis University (USA). Garland became a lecturer at the University of Toronto in 1951 and moved to Ottawa in 1952 to work at the Dominion Observatory. He got a professorship at the University of Alberta in 1954 and worked there until 1963, when J. Tuzo Wilson invited him to join the faculty of the University of Toronto. In 1959 Garland was elected Fellow of the Royal Society of Canada and served for the Society as its Foreign Secretary (1984–1986). Garland was IUGG Secretary General (1963–1973). (No image available)

Devendra Lal, IUGG President (1983–1987): Devendra Lal (India, 1929–2012) was a geophysicist. His works was in the field of cosmic radiation, physical and chemical processes on Earth and in the solar system, nuclear tracks and radioactivity in lunar samples and meteorites. He obtained his bachelor (1947) and master degrees (1949) from Banaras Hindu University in Varanasi, India, and PhD degree from the Tata Institute of Fundamental Research in Bombay (Mumbai) and Bombay University in 1960. He was appointed Professor in Nuclear Geophysics in 1967 and was Visiting Professor at Scripps Institution of Oceanography, University of California at San Diego, USA, divided his time between Scripps and appointments in India, first as a professor at the Tata Institute and then as professor and director of the Physical Research Laboratory in Ahmedabad (1972–1983), before making Scripps his full-time academic home (1989–2012). He was elected fellow of several national academies, including the Royal Society and US National Academy of Sciences. (Source: IUGG archives)

Vladimir I. Keilis-Borok, President (1987–1991): Vladimir Isaakovich Keilis-Borok (USSR, 1921–2013) was one of the most influential mathematical geophysicists of the last century. He graduated from the Moscow State Geological Prospecting University in 1943 and received his PhD (1948) and DSc (Habilitation, 1953) in mathematics and geophysics from the USSR Academy of Sciences in Moscow. He worked at the Academy's Institute of Physics of the Earth (1948–1989), and chaired its Department of Computational Seismology. In 1989, he founded the Institute of Earthquake Prediction Theory and Mathematical Geophysics at the Academy and was its first Director. In 1999, he moved to the USA to take a position of distinguished professor of UCLA. He was the founder of the IUGG International Committee for Geophysical Theory and Computers (1964–1979, now CMG), and served IUGG as a Bureau Member (1983–1987) and IASPEI Vice President (1983–1987). He was elected Ordinary Member of the ICSU Executive Board (1988–1991). Keilis-Borok was elected fellow of many national academies incl. the US National Academy of Sciences, Russian Academy of Sciences, Pontific Academy of Sciences, and Academia Europaea. (Courtesy of Alik Ismail-Zadeh)

Helmut Moritz, President (1991–1995): Helmut Moritz (Austria, born in 1933) is a physical geodesist. His work is in the fields of general geophysics, geodynamics, gravimetry, theoretical mechanics, and the theory of relativity. He graduated from the Graz University of Technology (TUG) in 1956 and obtained his doctoral degree in 1959 (TUG). Since 1955 he has held various positions at TUG, Geodetic Service of Austria, Ohio State University, Technical University Hannover, and Wuhan University. He was Professor of Physical Geodesy at the Technical University Berlin (1964–1971), and then Professor of Geodesy at the TUG Institute of Navigation (1971–2002), becoming Professor Emeritus at TUG. He was IAG President (1979–1983) and IUGG Bureau Member (1983–1991), and is an IUGG Fellow (2015). He was elected to the Austrian Academy of Sciences and several national academies. (Source: IUGG archives)



Peter J. Wyllie, President (1995–1999): Peter John Wyllie (USA, born in 1930, England) is a geophysicist and petrologist. He graduated from the University of St. Andrews (Scotland) in geology and physics, spending 1952–1954 as geologist with the British North Greenland Expedition. He has worked at St. Andrews, Pennsylvania State University, Leeds University, Penn State, the University of Chicago, and the California Institute of Technology (1983–1999), with terms as Department Chairman in Chicago (1979–1982) and Caltech (1983–1987), and Academic Officer at Caltech (1994–1999) until retirement. Wyllie has worked with many national and international committees and societies, culminating with 12 years on the IUGG Executive Committee (Vice President 1991–1995, President 1995–1999, Past-President 1999–2003; IUGG Fellow, 2015). Wyllie is a fellow or foreign member of several national academies, including the US National Academy of Sciences, Royal Society, Russian Academy of Sciences, Chinese Academy of Sciences, and Academia Europaea, and is an honorary fellow of several professional societies. (Source: IUGG archives)

Georges G. Balmino, Secretary General (1991–1999): Georges Balmino (France, born 1945 in Germany) is Emeritus Scientist at CNES and OMP (Observatory Midi-Pyrenees), Toulouse, France. He received a PhD in mathematics (1969) and a Habilitation degree in physics and astronomy (1973). He worked as a scientist at Meudon Observatory (1968–1972) and engineer then scientist at CNES and OMP (1973–2006): Head of Department of Terrestrial and Planetary Geodesy, head of the Space Geodesy group. Cofounder of the GOCE gravity consortium (European Space Agency). Director of Bureau Gravimetrique International (1979–1999); Executive Director, Groupe de Recherche de Geodesie Spatiale (1997–2004); Adjoint Professor, then Professor at Toulouse University (1974–1985). He is a member of Academia Europaea, Air & Space Academy, and Bureau des Longitudes, and fellow of AGU, IAG, and IUGG. (Source: IUGG archives)

6 Conclusion

IUGG of 1999 was remarkably different than IUGG of 1940 – a finding that applies generally to much of the geopolitical landscape. The seven International Associations remained intact (although several changed their names), but the scope of their scientific studies and their methodologies changed dramatically, especially with the advent of artificial satellites orbiting the Earth and extending into interplanetary space. International cooperation became commonplace after the success of the International Geophysical Year (1957–1958). The evidence for and discussion of global climate change began to permeate the General Assemblies. It was an exciting time for geodesy and geophysics.

Data availability. The paper is based on (i) published documents (see a list of references) as well as (ii) IUGG Archive documents. The original hard-copy documents of IUGG are deposited in the Niels Bohr Library and Archives of the American Institute of Physics (AIP, 2019). The documents are accessible only in the library with the permission of the IUGG Secretary General.

Appendix A

Table A1. IUGG General Assemblies from 1946 to 1999, and IUGG Presidents and Secretaries General elected.

No. GA	Year	Place	No. attendees	No. member countries	President	Secretary General
EO	1946	Cambridge, UK		36	Bjørn Helland-Hansen (Norway, 1946–1948)	James M. Stagg (UK, 1946–1951)
VIII	1948	Oslo, Norway	368	39	Felix A. Vening-Meinesz (the Netherlands, 1948–1951)	
IX	1951	Brussels, Belgium	918	44	Sydney Chapman (UK, 1951–1954)	Georges R. Laclavère (France, 1951–1963)
X	1954	Rome, Italy	923	47	Kalpathi R. Ramanathan (India, 1954–1957)	
XI	1957	Toronto, Canada	1165	54	John Tuzo Wilson (Canada, 1957–1960)	
XII	1960	Helsinki, Finland	1375	58	Vladimir Beloussov (USSR, 1960–1963)	
XIII	1963	Berkeley, USA	1938	58	Joseph Kaplan (USA, 1963–1967)	George D. Garland (Canada, 1963–1971)
XIV	1967	Zurich, Switzerland	2200	66	Jean Coulomb (France, 1967–1971)	
XV	1971	Moscow, USSR	2577	67	Henry Charnock (UK, 1971–1975)	George D. Garland (Canada, 1963–1971) Baron Paul Melchior (Belgium, 1973–1975)
XVI	1975	Grenoble, France	2564	72	Attia Ashour (Egypt, 1975–1979)	Baron Paul Melchior (Belgium, 1975–1991)
XVII	1979	Canberra, Australia	1944	75	George D. Garland (Canada, 1979–1983)	
XVIII	1983	Hamburg, Germany	3204	76	Devendra Lal (India, 1983–1987)	
XIX	1987	Vancouver, Canada	3939	76	Vladimir I. Keilis-Borok (USSR, 1987–1991)	
XX	1991	Vienna, Austria	4331	78	Helmut Moritz (Austria, 1991–1995)	Georges Balmino (France, 1991–1999)
XXI	1995	Boulder, USA	4481	79	Peter J. Wyllie (USA, 1995–1999)	
XXII	1999	Birmingham, UK	4052	76	Masaru Kono (Japan, 1999–2003)	Jo Ann Joselyn (USA, 1999–2007)

Appendix B

Table B1. AGU Geophysical Monograph series – IUGG Volumes.

No. IUGG Vol.	No. AGU Vol.	Title	Editors	Year of publication
1	46	Structure and Dynamics of Earth's Deep Interior	D. E. Smylie and Raymond Hide	1988
2	47	Hydrogeological Regimes and Their Subsurface Thermal Effects	Alan E. Beck, Grant Garven, and Lajos Stegena	1989
3	48	Origin and Evolution of Sedimentary Basins and Their Energy and Mineral Resources	Raymond A. Price	1989
4	49	Slow Deformation and Transmission of Stress in the Earth	Steven C. Cohen and Petr Vanfeek	1989
5	50	Deep Structure and Past Kinematics of Accreted Terrances	John W. Hillhouse	1989
6	51	Properties and Processes of Earth's Lower Crust	Robert F. Mereu, Stephan Mueller, and David M. Fountain	1989
7	52	Understanding Climate Change	Andre L. Berger, Robert E. Dickinson, and J. Kidson	1989
8	57	Evolution of Mid Ocean Ridges	John M. Sinton	1989
9	59	Variations in Earth Rotation	Dennis D. McCarthy and William E. Carter	1990
10	60	Quo Vadimus: Geophysics for the Next Generation	George D. Garland and John R. Apel	1990
11	69	Sea Level Changes: Determinations and Effects	Philip L. Woodworth, David T. Pugh, John G. DeRonde, Richard G. Warrick, and John Hannah	1992
12	72	Dynamics of Earth's Deep Interior and Earth Rotation	Jean-Louis Le Mouel, D. E. Smylie, and Thomas Herring	1993
13	73	Environmental Effects on Spacecraft Positioning and Trajectories	A. Valiance Jones	1993
14	74	Evolution of the Earth and Planets	E. Takahashi, Raymond Jeanloz, and David Rubie	1993
15	75	Interactions Between Global Climate Subsystems: The Legacy of Hann	Gordon A. McBean and M. Hantel	1993
16	76	Relating Geophysical Structures and Processes: The Jeffreys Volume	K. Aki and R. Dmowska	1993
17	82	Gravimetry and Space Techniques Applied to Geodynamics and Ocean Dynamics	Bob E. Schutz, Allen Anderson, Claude Froidevaux, and Michael Parke	1994
18	83	Nonlinear Dynamics and Predictability of Geophysical Phenomena	William I. Newman, Andrei Gabrielov, and Donald L. Turcotte	1994
19	150	The State of the Planet: Frontiers and Challenges in Geophysics	Robert S. J. Sparks and Christopher J. Hawkesworth	2004

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IUGG in the 21st century

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Abstract. The International Union of Geodesy and Geophysics (IUGG) has vigorously responded to a number of the natural, scientific, and technological challenges and driving forces that have marked the 21st century thus far. This paper reviews the actions of the Union that were precipitated by disasters caused by natural hazard events, climatic and environmental changes, and important scientific advances, as well as the opportunities to support International Years and other cooperative programs. This period has also given rise to a number of structural changes within the Union. IUGG added an eighth association, the International Association of Cryospheric Sciences, and inaugurated the new categories of affiliate and honorary memberships, introduced new grants, science education, and recognition programs, and formed new Union commissions on climatic and environmental change, data and information, planetary sciences, and a working group on history. Electronic communication was welcomed as a cultural norm. Overall, the development of the scientific landscape in the 21st century and a healthy future for the Union requires emphasis on fundamental Earth and space sciences as well as on transdisciplinary science to resolve urgent problems of society. IUGG will continue to evolve throughout the coming decades in step with the changing world of science and its international organizations, by responding to challenging problems as they arise.

1 Introduction

This is the last of three papers dedicated to the centennial history of the International Union of Geodesy and Geophysics (IUGG). The first paper (Ismail-Zadeh and Joselyn, 2019; current Special Issue) introduces the Union, presenting its mission, membership, structure, programs, products, and partners, and then presents an overview of the formation of the Union and its development until the beginning of WWII. The second paper (Joselyn and Ismail-Zadeh, 2019; current Special Issue) describes IUGG's evolution and its activities during the post-WWII era until the end of the 20th century.

Founded by nine scientific academies of the allied nations, the number of member countries increased to 35 by 1939 and to 76 by 1999, although some countries joined and left the Union over time; 22 general assemblies (and 2 extraordinary assemblies) were held in different international venues, and the number of delegates attending the general assemblies increased from a few dozen to more than 4000 scientists. Each General Assembly of the Union since the First General Assembly in 1922 until the XXII General Assembly in 1999 has been summarized by Ismail-Zadeh and Joselyn (2019) and Joselyn and Ismail-Zadeh (2019). The International Geophysical Year (IGY; 1957–1958) initiated by IUGG and its national members and co-sponsored by the International Council of Scientific Unions (ICSU; now the International Science Council – ISC) and the World Meteorological Organization (WMO) was an extraordinary global scientific effort. It was one of the most successful scientific and outreach programs of the last century, bringing together natural and social scientists, engineers, politicians, media, and society. After the IGY, international multi- and inter-disciplinary scientific campaigns became commonplace; many new international scientific bodies were formed by ICSU with IUGG's participation; many geophysical observatories were founded; and the Union initiated and rigorously supported a number of international scientific programs (see Table 1 in Joselyn and Ismail-Zadeh, 2019).

This paper starts with a review of the activities of the Union related to fostering research on disaster risks, and climatic and environmental changes. It discusses IUGG's involvement in and support of International Years and other cooperative programs during almost 2 decades of the 21st century (at the time of writing). A number of structural changes occurred within the Union, the most important of which was the establishment of the International Association of Cryospheric Sciences, an eighth association of the Union, in 2007. IUGG agreed to establish the new categories of affiliate and honorary memberships, introduced new grants, geoscience education, and recognition programs, and formed new Union commissions on climatic and environmental change, data and information, planetary sciences, and a working group on history. The development of the scientific landscape in this century and a healthy future for the Union requires emphasis on fundamental sciences as well as on transdisciplinary science to help in solving urgent problems of society.

2 Promoting natural hazards and disaster risk science

The early years of the 21st century have been marked by a number of extreme natural events and associated great disasters that have strongly influenced both public policy and scientific research (e.g., Cutter et al., 2015). These include earthquakes (e.g., 2004 Aceh-Sumatra in the Indian Ocean in 2005, Kashmir (Pakistan) in 2005, Wenchuan (China) in 2008, Haiti in 2010, Tohoku (Japan) in 2011, and Nepal in 2015) that triggered tsunamis and/or landslides; floods (e.g., in western and central Europe in 2002, China in 2007; Taiwan and Philippines in 2009); and cyclones and hurricanes (e.g., hurricanes Katrina in 2005 and Harvey in 2017, both in USA; cyclone Nargis in Myanmar in 2008). These and other extreme events have resulted in tragic losses of life and infrastructure.

Several of the IUGG Associations and inter-Association commissions address potentially violent geophysical processes. In August 2000, IUGG created the Union Commission on Geophysical Risk and Sustainability (GRC) specifically to study the likelihood of hazards, their impacts and consequences as a result of the vulnerability of societies, and to recommend measures for adaptation and mitigation. Thus, the commission was ready when a magnitude 9.2 earthquake struck on 26 December 2004 off the western coast of northern Sumatra, South Asia. The resulting tsunamis inundated the coastal zones around the Indian Ocean and resulted in losses of more than 230 000 lives across many countries. A few months before the event, the GRC had released the first catalog of tsunamis in the Indian Ocean to the public. The GRC, in cooperation with the IUGG inter-Association Tsunami Commission, prepared a statement that was sent to the Secretariat of the United Nations International Strategy for Disaster Reduction (UNISDR) and presented by IUGG Vice President Tom Beer to the United Nations World Conference on Disaster Reduction in Kobe, Japan (January 2005). This statement was revised and adopted as IUGG Resolution 8 "Reduction of Risk from Natural Hazards" at the General Assembly in Perugia, Italy, in 2007 (IUGG Archives, 2007). Several IUGG Associations responded by convening workshops and symposia to study the relevant geophysical process and presented recommendations for observation, analysis and warning systems. On 12 January 2010, a strong earthquake of magnitude 7 struck Port-au-Prince, Haiti, and resulted in a death toll that was estimated to range from 100 000 to 316 000. After the earthquake, on 29 January 2010, IUGG issued a special resolution, "Science on Natural Hazards and Environmental Disasters", urging the "international science community to quantify natural hazards and extreme events at all scales; to adopt integrative and comprehensive interdisciplinary approaches towards developing adaptation in order to decrease vulnerability; and to produce planning tools for disaster risk reduction at all scales." This and all other IUGG statements can be found on the IUGG website under Special Resolutions and Statements (http://www.iugg.org/about/special.php, last access: 29 January 2019).

A political consequence of scientific efforts to understand and predict natural disasters and inform society occurred in 2009 when the L'Aquila (Italy) Prosecutor's office indicted the members of the Abruzzi region's High Risk Committee for unintended murder for issuing statements to calm the population before the strong earthquake of 6 April that killed about 300 people. Believing that no scientist should be prosecuted for having expressed a scientific opinion based on available knowledge that is often necessarily limited, IUGG issued in June 2010 a statement on "Freedom to Conduct Science and Responsibilities of Scientists" highlighting the ICSU Principle of the Universality of Science. This principle encompasses freedom in relation to expressions of scientific ideas, hypotheses and forecasts, to conduct research using data, information, experiments and theories, and to communicate scientific results to the public through open publications and scientific conferences. Italy's Supreme Court finally cleared the committee's members in 2015, after a judicial process lasting more than 5 years (Cartlidge, 2015).

IUGG released two statements related to the eruptions of the Eyjafjallajökull volcano in Iceland that highlighted the importance of understanding the eruptive state of each of the world's active volcanoes for the safety and health of local residents as well as for air traffic and global climate. The first statement on Volcanic Ash Clouds (20 April 2010) was distributed at the Congressional Briefings on Reducing Volcano Risks in the U.S. Senate and the House of Representatives. The second statement on Volcanological and Meteorological Support for Volcanic Ash Monitoring (28 May 2010) was welcomed by the WMO Executive Board and the International Civil Aviation Organization (ICAO). Both statements can be found on the IUGG website, as specified above.

On 11 March 2011 a magnitude 9.0 earthquake occurred off the Pacific coast of Tohoku, Japan. It induced a catastrophic tsunami that hit the coasts of Tohoku and Kanto. The toll of dead and missing exceeded 18 000 people and critically damaged a Japanese nuclear power plant. IUGG expressed heartfelt sympathy for the victims, and again the GRC prepared a statement on the Great East Japan Earthquake and Tsunami that was adopted by the IUGG Bureau.

With the aim of strengthening international cooperation in disaster risk science, IUGG accepted a proposal by Secretary General Alik Ismail-Zadeh and initiated in 2010 an interdisciplinary international project entitled "Extreme Natural Hazards and Societal Implications – ENHANS" (http://www.icsu-geounions.org/enhans, last access: 29 January 2019), then co-sponsored by ICSU and several international and intergovernmental organizations. The major scientific results of the project were published in the IUGG volume Extreme Natural Hazards, Disaster Risks and Societal Implications (Ismail-Zadeh et al., 2014). The ENHANS project concluded that a reduction of disaster risk could be reached through in-depth scientific research on the topic and through disaster risk assessments.

In 2011, IUGG President Harsh Gupta and Secretary General Alik Ismail-Zadeh submitted a resolution on disaster risk assessment to the 30th ICSU General Assembly. The ICSU Executive Board then opened global discussions on the need for an intergovernmental body for the assessment of disaster risk and directed the preparation of a multi-disciplinary report that was presented at the 31st ICSU General Assembly (2014). The Assembly applauded the initiatives on disaster risk assessment undertaken by the Integrated Research on Disaster Risk (IRDR) program, ICSU, the International Social Science Council (ISSC), and the UNISDR, as well as the international scientific unions and the Council's Regional Offices, and invited individual national members to support the proposed intergovernmental disaster risk assessment process. After the ICSU General Assembly, ICSU and ISSC formed a joint ad hoc group of experts, co-chaired by ICSU President Gordon McBean and IUGG Secretary General Alik Ismail-Zadeh, to prepare a synthesis report on disaster risk research and risk assessment to be presented at the United Nations Third Conference on Disaster Risk Reduction held in Sendai, Japan, in 2015 (Ismail-Zadeh and Cutter, 2015). The report was published before the conference, and its executive summary was distributed among the delegates of the conference at the request of the Russian Federation.

3 Promoting climatic and environmental science

Among the environmental problems IUGG addresses are climate, its variability and the contribution of CO_2 emission to its change in order to save our planet for future generations; environmental pollution and its reduction in megacities to improve the quality of life; weather and water conditions to assist farmers during harvests and provide other indispensable ecosystem services; clean water and decontamination of polluted water to preserve and enhance human and ecosystem health; and pollution of oceans and seas, biodiversity and food security. Representing many disciplines of Earth and space sciences, IUGG has been continuously involved in projects and programs related to climatic and environmental changes and their impacts.

By the middle of the 20th century, the impacts of climatic and environmental changes were well understood by many experts involved in relevant studies and programs of ICSU or other international bodies (Weart, 2012). The experts proposed that a major scientific program on climate be established, and after long debates, the World Climate Research Programme (WCRP) was set up by WMO and ICSU in 1980 (later the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO) joined ICSU and WMO as a co-sponsor) in order to "determine the predictability of climate and to determine the effect of human activities on climate" (from the WCRP mission statement). IUGG experts contributed to the process of setting up the Intergovernmental Panel on Climate Change (IPCC) to help raise awareness of societies and politicians about climate change (Bolin, 2007). Among them was Bert Bolin (IUGG Bureau Member, 1963–1967), who was involved in setting up and development of the Global Atmospheric Research Programme (Ashford, 1982) as well as WCRP, the International Geosphere-Biosphere Programme, and IPCC, becoming its first Chairman (Rohde, 2013). Many IUGG experts shared the 2007 Nobel Peace Prize with the IPCC and Al Gore (Ismail-Zadeh, 2016).

In 2012, IUGG established the Union Commission on Climatic and Environmental Change (CCEC) to promote the advancement of scientific understanding of climatic and environmental change, to boost research in reducing uncertainties in climate and environmental models, to define criteria for collaborative transdisciplinary research on climate and environmental change, to fulfill the objectives of IUGG and its Associations, to provide an all-Union perspective on climatic and environmental change, and to make available the knowledge and insights developed through scientific research for the benefit of society and planet Earth, including consideration of the science of global change, related vulnerability and impacts, and potential responses. CCEC provides a focus for IUGG scientific expertise in climate and environment related areas across the breadth of all IUGG disciplines. CCEC enables the breadth of IUGG expertise to be brought to bear at the global level through collaborating with, and underpinning the work of ICSU and other international organizations. It also enables the geographic spread of IUGG expertise to be brought to bear at the local level through involvement with national bodies in the organization of scientific meetings and other activities. The research on the climatic and environmental change and high-impact of weather and climate events by the members of the CCEC and the Climate Commission of the International Association of Meteorology and Atmospheric Sciences (IAMAS) of IUGG was published as an IUGG volume by Cambridge University Press (Li et al., 2016). The work of CCEC demonstrated how multi- and inter-disciplinary research outputs from the geoscience community can be applied to tackle the physical and societal impacts of climate change and to contribute to Future Earth, a major environmental program initiated by the International Science Council (Beer et al., 2018).

At the request of IUGG Secretary General Alik Ismail-Zadeh, 14 international experts of the International Association on the Physical Sciences of the Oceans (IAPSO) of IUGG together with those of the ICSU Scientific Committee on Oceanic Research (SCOR) developed a synthesis report, Future of the Ocean and its Seas (Williamson et al., 2016), for science policymakers of seven economically developed countries (G7 Science Ministers). The report was prepared for the annual meeting of G7 Science Ministers held in Tsukuba, Japan, in May 2016, as a response of non-governmental scientific organizations to the concern of the policymakers expressed at their meeting in Berlin, Germany, in September 2015. The experts addressed topics related to plastic pollution of the marine environment, deep-sea mining and its ecosystem impacts, ocean acidification, deoxygenation, ocean warming, biodiversity loss, and marine ecosystem degradation.

4 International Years

The United Nations is the body that declares "International Years" (IY). The process requires both non-governmental and governmental support at the highest levels. To mark 50 years after the remarkable International Geophysical Year (1957–1958), 3 related IYs to conduct scientific programs were successfully proposed. These were the International Year of Planet Earth (IYPE), the International Polar Year (IPY), and the International Heliophysical Year (IHY). A fourth international program, the electronic Geophysical Year (eGY), joined the others to support this scientific focus. IUGG and the Union Associations were active in developing these programs and provided leadership and support for each. The four programs met in 2008 and issued the Tsukuba Declaration (http://www.egy.org, last access: 29 January 2019), noting that scientific cooperation among the global science community, national academies of sciences, research funding agencies, industry, national governments, and inter-governmental bodies provide society and its leaders with the best possible information to make decisions on a sustainable future for humankind. Table 1 lists the International Years initiated and/or supported by IUGG since 2001.

5 GeoUnions

In 2004, representatives of several ICSU International Scientific Unions dealing with Earth and space sciences met in Paris to establish a partnership to better promote the geosciences worldwide, to communicate and to coordinate scientific activities of individual unions, and to gain recognition by ICSU bodies, the United Nations organizations, and other global stakeholders. The partnership has endured as the GeoUnions. Current members are the International Astronomical Union, the International Cartographic Association, the International Geographical Union, the International Union for Quaternary Research, the International Society for Photogrammetry and Remote Sensing, IUGG, the International Union of Geological Sciences, the International Union of Soil Sciences, and the International Union of Radio Science.

The GeoUnions Steering Committee has developed a website (http://icsu-geounions.org, last access: 29 January 2019) to inform the scientific community about joint activities. The GeoUnions network has persisted and has proved powerful in fostering integrated interdisciplinary research. An example of one such collaboration is the Geoscience in Africa initiative, launched in 2003 by then IUGG President Uri Shamir, based on the recognition that geophysical processes are global and that African scientists suffer, more than others in the rest of the world, from shortage of resources, shortage of an adequate cadre of trained scientists, and lack of government recognition and support. Adopted as a science program of the GeoUnions, this effort supported the ICSU Regional

Table 1. International Years initiated or supported by IUGG (2000–2019).

International Year of Planet Earth (IYPE; 2007–2010)	IYPE (http://yearofplanetearth.org, last access: 29 January 2019) was the first UN Year for Earth Sciences initiated and led by the International Union of Geological Sciences. In December 2005, the UN General Assembly proclaimed 2008 as the UN Year of Planet Earth – Earth Sciences for Society. IUGG had supported the drive toward IYPE since 2003. Nine science objectives and relevant teams were established: hazards (chaired by Tom Beer, IUGG President 2007–2011); groundwater; climate; oceans; Earth and health; resources; megacities; deep Earth; and soils. IUGG scientists were valued members of many of these teams. A series of monographs were published that report on each of these topics (https://link.springer.com/bookseries/8096, last access: 29 January 2019).
International Polar Year (IPY; 2007–2008)	Previous IPYs (1882–1883, 1932–1933, and IGY 1957–1958) successfully promoted unprecedented exploration and discoveries, and fundamentally changed how science was conducted in Polar Regions. The fourth IPY (http://ipy.org, last access: 29 January 2019) brought together tens of thousands of investigators to collect and analyze data in diverse disciplines in the physical, life, and social sciences, including engagement of the native communities. The IPY Data and Information Service (IPYDIS) addressed the challenge of data coordination. The IPYDIS participated in the IUGG-led Electronic Geophysical Year (eGY) and applied eGY principles to IPY data management. Building on the precedent set by the Antarctic Treaty, the data generated during the campaign have been archived in the Polar Information Commons, an open-access information resource about the Earth's polar regions (http://www.polarcommons.org, last access: 29 January 2019). Major publications and conferences emerged from the IPY. The final IPY conference, From Knowledge to Action, was held in Montréal, Canada in 2012.
Electronic Geophysical Year (eGY; 2007–2008)	Initiated by the International Association of Geomagnetism and Aeronomy (IAGA), the opening ceremony was held during the IUGG General Assembly in Perugia, Italy in 2007. The Electronic Geophysical Year (http://www.egy.org, last access: 29 January 2019) provided the international framework for mobilizing the science community to achieve a step increase in making past, present, and future geoscientific data readily, rapidly, conveniently, and openly available. The eGY promoted the development of a network of virtual observatories and focused on themes of electronic data location and access, permission and release of data, conversion of data into modern digital form, data preservation, outreach, and capacity building in developing countries, especially in Africa.
International Heliophysical Year (IHY; 2007–2008)	Several IAGA commissions participated in this broad international effort which addressed all aspects of the connected Sun-Solar system while also engaging the public, and students all over the world. It was coordinated with the UN Basic Space Science Initiative through their Office for Outer Space Affairs. The IHY Organizing Committees included 75 nations, and the activities involved representation from nearly all of the 192 United Nations member states. More information on the IHY and its legacy, the International Space Weather Initiative, can be found at: http://www.unoosa.org/oosa/en/ourwork/psa/bssi/ihy2007.html (last access: 29 January 2019).
International Year of Deltas (IYD; 2013–2014)	This year focused on the value and vulnerability of river deltas worldwide. IYD was co-sponsored by IUGG under the auspices of the International Association of Hydrological Sciences (IAHS) and the International Association for the Physical Sciences of the Oceans (IAPSO), who appointed liaisons to the IYD Scientific Committee. It was extended in 2015 to the International Decade of Deltas program. More information on the IYD: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2011EO400006 (last access: 29 January 2019).
International Year of Global Understanding (IYGU; 2016–2017)	Co-sponsored by IUGG, IYGU was initiated by the International Geographical Union and endorsed by ICSU, ISSC and the International Council for Philosophy and Human Sciences (CIPSH). IYGU aimed to build bridges between global thinking and local action by addressing sustainable development and fostering policies on critical global challenges such as climate change, food security and migration. In 2018, this year was extended to the International Decade of Global Understanding program. More information on the IYGU: http://www.global-understanding.info/ (last access: 29 January 2019).

Office in Africa, and "eGYAfrica – better Internet connectivity for research and education institutions in Africa", and the ENHANS project noted above. Current key areas are disaster risk reduction and the International Year of Global Understanding (IYGU).

6 IUGG structure

A significant change to the IUGG structure in the 21st century was the addition of an eighth Association, the International Association of Cryospheric Sciences. The new Association had its origins in the IAHS International Commission on Snow and Ice (ICSI), formally established in 1948 but with roots extending back to 1894. At the 2004 IUGG Executive Committee meeting, a Union Commission for the Cryospheric Sciences (IUGG/CCS) was proposed by IAHS and supported by IAMAS, IAPSO, and IAVCEI. The Commission began work on its proposed Association Statutes and By-laws, organized international symposia and planned scientific sessions for the 2007 IUGG General Assembly. In the meantime, changes in the IUGG Statutes and By-laws and other administrative and financial procedures were prepared to make way for a new Association. By action of the IUGG Council on 4 July 2007, the new Association was welcomed into the IUGG family.

After the General Assembly in Birmingham, UK (1999), election procedures for IUGG officers were modified to allow additional nominations following the report of the Nominating Committee. At the General Assembly in Perugia, Italy (2007), the duties of the Bureau, the Secretary General and the Treasurer with regard to the administration were refined, and Statute 27 was modified so that while French and English are the official languages of the Union, the English version of the Statutes is now the definitive version of the text. The membership and duties of the Finance Committee were addressed at the 2003 and 2011 General Assemblies, and at the General Assembly in Melbourne, Australia (2011), IUGG Honorary membership (Fellows) was instituted to honor individuals for their exceptional contribution to Earth and space sciences or international cooperation in geodesy or geophysics.

At the General Assembly in Prague, Czech Republic (2015), the composition of National Committees was clarified in order to advance the participatory culture of the Union and improve transparency. Also in Prague, it was decided that delegates to the IUGG Council should be appointed by the Adhering Bodies of Member Countries for the period between General Assemblies (normally for 4 years) so that the Council could vote electronically and make decisions between General Assemblies. This provision permitted the IUGG Bureau to propose several changes to the Statutes and By-laws following the Prague General Assembly. After consultations with the IUGG Council, the changes were approved unanimously on 5 April 2018 by electronic ballot. The position of Vice President was replaced by President-elect, who then becomes President of the Union in the following term of office. The number of members of the Finance Committee was reduced from four to three people and the terms of office of the Secretary General, Treasurer, Bureau Members at large and Finance Committee members were redefined. The vote of the immediate Past President at the Executive Committee was restored.

7 IUGG membership and finance

The IUGG Council has approved a number of changes regarding membership since 1999. At the General Assembly in Birmingham, UK in 1999, the category of Associate Membership (characterized by exemption from paying annual dues) was created; Associate members were not allowed to sit in Council meetings (as opposed to members with Observer status, who could attend Council meetings but not vote). A By-law change clarified that scientists from all countries could attend scientific meetings of the Union and of the Associations and participate as observers in Commissions of the Union and in the Associations. At the General Assembly in Sapporo, Japan (2003), it was decided that one delegate from each Associate member country could attend Council meetings as listeners only. It was also agreed that other "Listeners" could attend Council meetings with the permission of the President, although a vote of Council members could exclude Listeners if appropriate. At the General Assembly in Perugia, Italy (2007), the number of financial categories to determine membership dues was increased to 14. At the General Assembly in Melbourne, Australia (2011), Affiliate membership was added to provide a mechanism to formalize linkages with various international and regional organizations dealing with Earth and space sciences, and the Statutes and By-laws were clarified with regard to Associate and Observer membership status. At the General Assembly in Prague, Czech Republic (2015), a change was made to allow a representative of an Associate Member to speak (without the right to vote) at Council meetings, and individuals from countries in Associate or Observer status or from non-Member countries could be elected to Association office (except for the position of the Association President because the Association President is a member of the IUGG Executive Committee).

As of 1 January 2019, IUGG had 72 National Members (see Appendix A for the IUGG Members since 1919, and Table 2 for the changes in the number of members for the last 20 years). The paying members are placed in categories from 1 to 14 depending on their financial contribution to the Union (the membership dues rise with increasing category number). At present, the highest category used is category 11. The members pay dues according to a number of units assigned to their category (in category 1 the number of units is 1, and in category 11 the number is 35). According to

Table 2. IUGG General Assemblies (GA) from 1999 to 2019, and IUGG Presidents and Secretaries General elected.

No. GA	Year	Place	No. of attendees	No. of Member countries	President	Secretary General
XXIII	2003	Sapporo, Japan	4151	65	Uri Shamir (Israel, 2003–2007)	Jo Ann Joselyn (USA, 1999–2007)
XXIV	2007	Perugia, Italy	4375	66	Tom Beer (Australia, 2007–2011)	
XXV	2011	Melbourne, Australia	3392	70	Harsh Gupta (India, 2011–2015)	Alik Ismail-Zadeh (Germany/Russia, 2007–2019)
XXVI	2015	Prague, Czech Rep.	4231	71	Michael Sideris (Canada, 2015–2019)	
XXVII	2019	Montreal, Canada		72		

a decision made at the XXII IUGG General Assembly in Boulder, USA (1995), the price of 1 unit is determined every year using an inflator index obtained from the Bureau of Labor Statistics, U.S. Department of Labor. The funds received as dues are the basis for IUGG's operations as a scientific union, although Union Associations may have their own funds earned through donations, book sales, or other fundraising efforts. The funds are spent to support scientific activities of Union Associations and Commissions; international scientific programs, projects and services; general and scientific assemblies and other meetings; the IUGG Grants and Geoscience Education programs; the International Lithosphere Program; the International Science Council; travel of students, early career scientists, and scientists from developing countries to attend scientific meetings; and administration and management.

8 The IUGG Secretariat

The IUGG Secretariat has undergone significant changes to allow for modern governance, especially making use of the World Wide Web and digital technologies. The Union has had a web site since 1999 maintained by a web-master located in France (1999–2000, 2005–2007), USA (2000–2005), and Russia (since 2007), and overseen by the IUGG Secretary General. The IUGG Yearbook was first published electronically in 2004. Annual reports since 2001 (and earlier as digital scans become available) are also posted online. Since November 2014, the Secretariat has used web-conferencing software to support real-time communications between IUGG Bureau and Executive Committee Members through text-based instant messages, voice and video chat, online presentations, web conferences, and desktop sharing. This technology increases communication and productivity, conserves time and reduces travel expenses, and accelerates the decision-making process. IUGG is on Twitter (https://twitter.com/theiugg, last access: 29 January 2019) and Facebook (https://www.facebook.com/InternationalUnionGeodesyGeophysics, last access: 29 January 2019).

The IUGG Electronic Journal began monthly publication on 1 February 2001, as a means to communicate the actions of the Union and the Associations. A web-based IUGG Central Electronic Library (CEL) was established (2013) to stimulate the exchange of scientific knowledge by (i) archiving, (ii) presenting, and (iii) publishing IUGG-related documents; at present one single platform for all of this is under construction. IUGG-related documents include reports, yearbooks, e-journals, newsletters, conference abstracts, oral/poster presentations, and more, originating from IUGG and its Union Associations, Union Commissions, Committees, Liaisons, Research Programs, and Science Education Events. New digital IUGG-Association logos were professionally designed and approved by the Executive Committee in December 2016.

From mid-1999 to 2007 the office of the IUGG Secretary General was hosted by the University of Colorado at Boulder, USA, within the Cooperative Institute for Research in Environmental Sciences (CIRES). The IUGG Secretariat moved to Karlsruhe, Germany in 2007, where it was hosted by the Geophysical Institute at the Karlsruhe Institute of Technology (KIT; former Karlsruhe University). On 7 June 2013, at the invitation of Reinhard Hüttl, Scientific Executive Director of the GFZ German Research Centre for Geosciences (GFZ-Potsdam), the office of the IUGG Secretariat was relocated to Potsdam, Germany. Salary and facilities for an Executive Secretary (Assistant Secretary General) to support the Secretariat are provided by the GFZ-Potsdam. Additional financial support to the Secretariat comes from the German Research Foundation (DFG), which provides funds for the position of Assistant of the Executive Secretary and for business travel of the IUGG Secretary General.

The IUGG historical records were transferred in 2001 to the Niels Bohr Library of the Center for the History of Physics of the American Institute of Physics. The historical records consist of documents and correspondence dating

Figure 1. Opening ceremony of the XXIII IUGG General Assembly. Seiya Uyeda, Chair of the Local Organizing Committee (welcoming the Assembly's participants) on the left, and His Majesty The Emperor of Japan and The Empress of Japan on the right of the photo (courtesy: S. Uyeda).

from the origin of the Union in 1919, and extending into the mid-1990s; additional material was sent in December 2007 (AIP, 2019).

9 Highlights of IUGG General Assemblies

As the 21st century began, the actions from the XXII General Assembly held in Birmingham, UK, in 1999 were in place. There was one change in the officers of the Bureau elected in Birmingham: L. Vere Shannon (South Africa) resigned, and by action of the Executive Committee, was replaced by Tom Beer (Australia).

9.1 XXIII General Assembly (30 June–11 July 2003, Sapporo, Japan)

IUGG President Masaru Kono (Japan) presided. Vice President was Uri Shamir (Israel), Secretary General was Jo Ann Joselyn (USA), Treasurer was Aksel W. Hansen (Denmark), and Bureau members were Junyong Chen (China), Harsh Gupta (India), and Tom Beer (Australia). This was the first IUGG General Assembly to be held in Asia. His Majesty The Emperor of Japan addressed the Opening Ceremony (Fig. 1). Seiya Uyeda chaired the Local Organizing Committee, and Atsuhiro Nishida chaired the Scientific Programme Committee. The theme of the General Assembly was "State of the Planet: Frontiers and Challenges", and featured four Union lectures and 182 scientific sessions including eight Union Symposia. The IUGG volume "The State of the Planet: Frontiers and Challenges in Geophysics" was published in the AGU Geophysical Monograph series (Sparks and Hawkesworth, 2004). Attendance was impacted by a serious global outbreak of the Sudden Acute Respiratory Syndrome (SARS); some had to delay or cancel travel arrangements due to precautionary requirements.

Three special committees presented reports: IUGG Structure, Goals, and Objectives; IGY+50, which began as a simple celebration but culminated in four major international programs as described earlier: eGY, IHY, IPY, and IYPE. A special Union Symposium "Geosciences – The Future" was presented by a working group of young scientists that was initiated by Vice President Uri Shamir, to stimulate involvement and leadership by early career scientists. A discussion of IUGG Structures, Goals, and Objectives centered on the responses to questionnaires that had been submitted to the IUGG Adhering bodies, National Committees, and Associations. An addition to Council business was an informal meeting of the delegates led by Ronald Stewart (Canada) during which delegates could freely express ideas and opinions.

During this quadrennium, IUGG allocated financial support for meeting attendance and inter-Association initiatives to benefit developing countries (22 meetings, workshops and schools in 17 different countries), as well as interdisciplinary and inter-Union initiatives that particularly benefited developing countries. ICSU also awarded grants to promote Association research objectives.

Resolutions (IUGG Archives, 2003) were adopted that supported geophysical seafloor observations, ocean modeling, a geodetic observing system, Earth monitoring with synthetic aperture radar, data access under the Comprehensive Nuclear-Test-Ban Treaty (CTBT), and the need for release of airborne and marine magnetic data.

9.2 XXIV General Assembly (2–13 July 2007, Perugia, Italy)

IUGG President Uri Shamir (Israel) presided. Vice President was Tom Beer (Australia), Jo Ann Joselyn (USA) continued as Secretary General, Aksel W. Hansen (Denmark) as Treasurer, and Bureau members were Yun-tai Chen (China), Harsh Gupta (India), and Ali A. A. Tealeb (Egypt). Held in the historic Umbria Region of Italy, Lucio Ubertini chaired the Local Organizing Committee and Paola Malanotte-Rizzoli chaired the Scientific Program Committee. The theme was "Earth: Our Changing Planet", and the Assembly featured four Union lectures, thirteen Union symposia, and 187 Association and inter-Association symposia and workshops.

The International Association for Cryospheric Sciences (IACS) became the 8th IUGG Association (Fig. 2). A new document, Guidelines on IUGG Administration, was introduced. The 50th anniversary of the IGY was celebrated, and the eGY was inaugurated, joining the other IGY+50 scientific programs: IHY, IPY, and IYPE.

During the preceding 4 years, IUGG allocated funds to the organizers of 32 symposia, workshops, schools or meetings in 25 different countries, most of them developing countries. In addition, grants were allocated in the years 2004 and 2005 to support eight inter-Association initiatives that specifically benefited developing countries. By action of the 2005 Executive Committee, the grants were suspended for 2006–2007 in order to build a reserve that could be used to seed potential initiatives under Geosciences in Africa. This program, adopted by the GeoUnions, cooperated with the ICSU Regional Office in Africa and supported the eGY-Africa program to help to reduce the digital divide through better Internet access for scientists (and others) in universities and similar institutions in Africa. In addition, IUGG supported inter-Union activities, including ILP, WCRP, and the Federation of Astronomical and Geophysical Data Analysis Services (FAGS). IUGG received competitive grants from ICSU to promote IAGA and IAHS research objectives, nominated persons for numerous panels and working groups, and endorsed the ICSU "Agenda for Action" with regard to Science in the Information Society.

Resolutions (IUGG Archives, 2007) adopted included support of an International Astronomical Union's resolution on nomenclature and definition of TDB (Temps Dynamique Barycentrique); support of Geocentric and International Terrestrial Reference Systems (GTRS and ITRS) and the Global Geodetic Observing System (GGOS); eGY and Data Rescue; Ionosphere Satellites; The Urgency of Addressing Climate Change; Intensified Study of Aerosol Pollution Effects on Precipitation; and Reduction of Risk from Natural Hazards.

Figure 2. IUGG's congratulations on the occasion of the birth of IACS. Featured is Georg Kaser, the first IACS President (source: IUGG archives).

9.3 XXV General Assembly (27 June–8 July 2011 – Melbourne, Australia)

IUGG President Tom Beer (Australia) presided. Vice President was Harsh Gupta (India), Secretary General was Alik Ismail-Zadeh (Germany/Russia), Aksel W. Hansen (Denmark) continued as Treasurer, and Bureau members were Yun-tai Chen (China), David Jackson (USA), and Ali A. A. Tealeb (Egypt). This was the second IUGG General Assembly to be held in Australia, and the third time it was held outside of Europe and North America. Ray Cas chaired the Joint Australia and New Zealand Organizing Committee and Peter Manins coordinated the Scientific Program Committee. The theme was "Earth on the Edge: Science for a Sustainable Planet", and the Assembly featured nine Union lectures and a total of 198 symposia and workshops.

The Royal Society (the UK Adhering Body to IUGG) developed a program to engage African scientists in the work of ICSU international unions, and paid for 3-year membership dues of the Democratic Republic of Congo, Ghana, and Morocco, IUGG Associate Members, allowing them to participate in full in Union's activities. IUGG co-sponsored and took an active part in the international programs dedicated to the 50th anniversary of the IGY. Association scientific assemblies were held in Reykjavík, Iceland (IAVCEI); in Cape Town, South Africa (IASPEI); MOCA, a joint assembly of IAMAS, IAPSO and IACS was held in Montreal, Canada; IAGA held its assembly in Sopron, Hungary; IAG met in Buenos Aires, Argentina; and IAHS held its assembly together with the International Association of Hydrogeologists in Hyderabad (India). The IUGG Union Commissions organized several conferences and symposia: two CMG conferences on mathematical geophysics in Longyearbyen (Norway), and in Pisa (Italy), two SEDI conferences in Kunming (China), and Berkeley (USA), and three GRC symposia in Barcelona (Spain), Oslo (Norway), and Torino (Italy). GRC took active part in the organization and running of the ICSU-sponsored ENHANS project events in Iguassu (Brazil), San Francisco (USA), Pretoria (South Africa), Antalya (Turkey), and Melbourne (Australia). A new Union Commission for Data and Information was set up to provide a focused and sustainable organizational structure that supports and strengthens IUGG science through integrated scientific information activities. Four new Union Committees on Capacity Building and Education, Honours and Recognition, Membership Issues, and Visioning were set up to increase IUGG visibility worldwide.

Seven multi- and inter-disciplinary international scientific projects were supported through the IUGG Grants Program. IUGG meeting support was allocated to the organizers of 43 symposia, workshops, schools or meetings in 31 different countries, most of them in developing countries. ICSU competitive grants were awarded to promote research on natural hazards and disaster risks as well as geophysical research and geoinformation in Africa. IUGG also supported inter-Union activities, including ILP, the WCRP, and FAGS, now transformed into the World Data System (WDS).

Resolutions (IUGG Archives, 2011) that were adopted included the issue of standardizing terminology for glacier mass balance measurements and for classification of snow on the ground; endorsement of the International Celestial Reference Frame; the need for gravity and magnetic field satellite missions; and adoption of the International Thermodynamic Equation of Seawater – 2010 (TEOS-10). It was noted that the IUGG Executive Committee had adopted several resolutions and statements during the inter-General Assemblies period with regard to several natural disasters (noted elsewhere).

9.4 XXVI General Assembly (22 June–2 July 2015, Prague, Czech Republic)

IUGG President Harsh Gupta (India) presided. Vice President was Michael Sideris (Canada), Secretary General was Alik Ismail-Zadeh (Germany/Russia), Aksel W. Hansen (Denmark) was Treasurer, and Bureau members were Isabelle Ansorge (South Africa), Pierre Hubert (France), and Kenji Satake (Japan). Prague was the only city to host the IUGG Assembly for the second time, having hosted the Third IUGG General Assembly in 1927. Vladimir Cermak chaired the Local Organizing Committee and Eduard Petrovsky chaired the Scientific Program Committee. The Theme of the General Assembly was "Earth and Environmental Sciences for Future Generations". There were nine Union lectures and 11 Union symposia; Nobel Prize winner Yuan Tseh Lee presented a Union lecture on "Transformation of human society for sustainable future." The scientific program included 198 symposia and workshops.

The Visioning Committee prepared, and the delegates approved, a draft Strategic Plan for 2016–2023 to be developed along with a plan for implementation (the final plan was approved by the Council by electronic ballot in 2016; the implementation actions were approved by the Bureau in 2017). A new category of Union Membership, Affiliate, was established to strengthen cooperation with geoscientific organizations worldwide. Since 2012, six scientific organizations became IUGG Affiliate Members: the Commission for the Geological Map of the World, the Young Earth Scientists Network, the American Geosciences Institute, the International Association for Mathematical Geosciences, the International Landslides Consortium, and the International Association for Geoethics.

The first IUGG awards were presented (Fig. 3). The full list of IUGG Early Career Scientist Awards, Elected Fellows who have made outstanding contributions to geodesy and geophysics, and Conferred Fellows honored for service as officers of IUGG and the Associations, is maintained on the IUGG website. The IUGG Gold Medal was awarded to Sir Brian J. Hoskins (UK) for "his scientific contributions that have been pioneering and profound in almost all aspects of the atmospheric and climatological sciences, with strong linkages to IUGG and its Associations."

An agreement was signed with Cambridge University Press to develop a new series of special publications of IUGG to publish peer-reviewed books on perspectives and reviews in multidisciplinary research. The first volume of this series, "Extreme Natural Hazards, Disaster Risks and Societal Implications", was published in 2014 (Ismail-Zadeh et al., 2014), the second volume, "Dynamics and Predictability of Large-Scale, High-Impact Weather and Climate Events", in 2016 (Li et al., 2016), and the third volume, "Global Change and Future Earth", in 2018 (Beer and Alverson, 2018). IUGG established a new Science Education Program to enhance geophysical and geodetic science education. In 2012–2015, IUGG funded 24 advanced schools and workshops at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy. ICSU grants promoted geophysical research in Africa and funds to network the magnetic community in the northern Indian Ocean region. Also, nine interdisciplinary international scientific projects were supported through the IUGG Grants Program.

In 2013 IAVCEI proposed to open membership of IUGG to individual scientists at the same time as the IUGG Executive Committee was discussing various possibilities for individual Union membership. Based on the majority of the opinions from Union Associations and National Members, the IUGG Executive Committee agreed that the Union should continue with National, Affiliate, and Honorary Memberships, and each Union Association may introduce individual membership programs to allow active scientists from non-Member countries to participate in activities of Associations. Association scientific assemblies were held on several continents in 2013: the joint Scientific Assembly DACA-

Figure 3. Award ceremony at the XXVI IUGG General Assembly, Prague, Czech Republic, 2015.

13 of cryospheric (IACS) and atmospheric (IAMAS) scientists in Davos, Switzerland; the IAGA Scientific Assembly in Merida, Mexico; the joint Scientific Assembly of hydrologists (IAHS), oceanographers (IAPSO) and seismologists (IASPEI) "Knowledge for the Future" in Gothenburg, Sweden; the IAVCEI Scientific Assembly in Kagoshima, Japan; and the IAG Scientific Assembly in Potsdam (Germany) celebrating the 150th anniversary of the association. The IUGG Union Commissions organized seven scientific events in Asia, Europe, and North America. The Union cosponsored 43 international scientific events.

Resolutions (IUGG Archives, 2015) that were adopted included the Role of Ocean in Climate, Future Satellite Gravity and Magnetic Mission Constellations, the Global Geodetic Reference Frame, Real-time GNSS (Global Navigation Satellite System) Augmentation of the Tsunami Early Warning System, and cooperation in Geo-energy Resources and International Scientific Activities.

The members of the Bureau for the ensuing quadrennial were elected: President Michael Sideris (Canada); Vice President Kathryn Whaler (UK); Secretary General Alik Ismail-Zadeh (Russia/Germany); Treasurer Aksel W. Hansen (Denmark); Bureau Members: Isabelle Ansorge (South Africa), Pierre Hubert (France) and Chris Rizos (Australia). A vote of the delegates selected Montreal, Canada, as the venue of the XXVII IUGG General Assembly (8–18 July 2019).

10 IUGG tomorrow

IUGG is entering its second century. A healthy future for the Union requires emphasis on basic Earth and space sciences as well as science for society. The landscape of Earth and space sciences is changing: we are witnesses of pressing challenges, such as sprawling towns and the growth of megacities, climatic and environmental change; ocean acidification and sea pollution; disasters due to natural and human-induced hazards and associated losses due to vulnerability of societies; unsustainable land use; food insecurity; and depletion and scarcity of mineral resources and water. The importance of scientific understanding of the urgent problems of society has never been greater, as humanity engages in the problems of living sustainably on planet Earth. Governments, funding agencies, international and national organizations, professional societies and international unions are dedicating more attention to the aspects of research related to the environment, renewable natural resources, clean water, disaster reduction, resilience and others. To address these challenges, the scientific community decided in 2017 to form a new council, the International Science Council (ISC), merging ICSU and ISSC, to create a unified, global voice of science with a powerful presence in all regions of the world and representation across the natural and social sciences. As a founding member of ISC, the Union has a responsibility to ensure that its activities align with the ISC's agenda.

10.1 Basic research

Geoscientists need to continue to put their basic results to use, and inter- and trans-disciplinary (ITD) approaches are vital to making progress in science for society. The coupling between the spheres of the Earth and space sciences as well as between those and social sciences is often lost. Integrated research combining expertise from relevant disciplines will help quantify the observed processes and, more importantly, elucidate which interactions between spheres are essential. According to Adams (2013), the best science results from international collaboration, and hence IUGG should think about new ways and incentives to enable more scientists to participate in international networks. This need for increased collaboration is set against changes in the current science landscape and sociopolitical environment that make international cooperation more difficult. Given these realities, IUGG will have to work especially diligently to adapt to this new environment and promote cooperation.

10.2 Data issues

The Internet and advances in technology have been enhancing the ability of scientists to collect, archive, and distribute data across all fields and nations. Strengthening norms around openly accessible research and broadening global access to data, digital technologies, and reliable internet connections would be a boon would be a boon to scientists in developing countries and to independent/unaffiliated scholars everywhere, enabling them to further advance their own research thanks to prompt and equal access to advanced datasets and model results. In order to make the promises of the digital age a reality, existing geodetic and geophysical data centers and data services should be expanded, and new multi-disciplinary data centers and data services should be established to enable scientists to work in interdisciplinary areas with unrestricted access to data for scientific research. Also, such centers could make data produced with public participation (sometimes called "citizen science" data) more valuable, e.g., ash samples collected after the 2010 eruptions of Eyjafjallajökull in Iceland or felt earthquake information.

A significant challenge facing geosciences is to combine "big data" (that is, the large volume, high velocity and/or variety data assets that demand modern forms of processing enabling deep insight and decision making) with state-of-the-art models for better understanding of nature's complex systems. This will be a key component of progress in geosciences in the near future. IUGG, via its permanent geodetic and geophysical services, should continue to promote the development of existing and new sophisticated, cutting-edge methodologies and tools in data collection, transmission, analysis, and dissemination of outputs to help address challenging problems in Earth and space sciences. IUGG's role in promoting an open data policy as well as the activities of observational and data services and in encouraging international investment in observing systems is, and will continue to be, important. We envisage that IUGG will enhance its working relationship with such bodies as the intergovernmental Group on Earth Observations (GEO), CODATA and WDS to promote data curation and openness and data analysis for new discoveries. Knowledge transfer can be accomplished successfully by utilizing mass media outlets as well as by traditional ways of cooperation with policymakers. The web and social media are the best ways to reach the youth audience, a key demographic in ensuring the future of geoscientific research, as well as a broader audience more generally, including communities that may not have had much access to advanced scientific findings in the past (e.g, communities lacking financial or scholarly resources).

10.3 Interdisciplinarity

Societal problems need an integrated, trans-disciplinary scientific approach (e.g., Ismail-Zadeh et al., 2017). The way forward for IUGG and other scientific unions and professional societies is to foster fundamental science for new discoveries and promote co-designed/co-productive ITD research. IUGG should place an emphasis on scientific investigations for interventions, that is, foster action-oriented solutions of societal problems. For example, for disasters caused by natural hazard events, relevant research can be integrated and co-produced. A way of integration and co-production could be through the maturation of disaster science and through trans-disciplinary approaches aiming at in-depth investigations using systems analysis approaches. Systems analysis allows a disaster and/or disaster risk problem to be decomposed into its component parts to study how well they work, interact, and contribute to the overall aim of risk reduction. The final goal of the ITD approach is to issue recommendations for actions to reduce risks and to improve societal resilience (Cutter et al., 2015). Hence, IUGG should promote both disciplinary and ITD approaches in science education. Training and education within geoscience as well as practice domains can, through co-engaged and co-produced knowledge, enhance our understanding of the needs of vulnerable regions and populations, and enable practitioners and policymakers to use it to better effect.

One of the needs for co-productive research is to evaluate the quality and the success of ITD studies (NAS, 2004). IUGG has a role to play in such assessments. Together with other international scientific bodies, IUGG can lead in proposing and developing norms for ITD practice and geoscience education. For example, IUGG might develop appropriate standards and relevant skills to be mastered by students and scientists who participate in ITD education and research. The Union, via National Committees, could lobby national funding agencies to support ITD research projects and promote success stories of international ITD findings.

10.4 Future of international scientific organizations

Looking into the future, one may ask: does modern science need international non-governmental organizations? Can the national and regional organizations replace them? What would happen if international scientific unions disappear? Historically, IUGG and other international scientific unions were set up as a response to the need for cooperation between nations, as many aspects of geosciences required international collaboration. Neither national nor regional professional societies (e.g., the American Geophysical Union (AGU), the Asia Oceanic Geosciences Society (AOGS) or the European Geosciences Union (EGU)) can truly replace international unions, as national and regional societies' major concern is typically their own nation or geographical region. Three possible scenarios could be drawn up for future development of IUGG and other international unions (Ismail-Zadeh, 2016): (1) integration of international geoscientific unions (e.g., GeoUnions of the ISC) and professional societies of geoscientists (e.g., AGU, AOGS, EGU); (2) reshaping of scientific priorities and structures of current geoscience organizations and their independent development in a cooperative way; and (3) competition between international, regional and national unions and societies.

The first scenario could possibly lead to the development of an international geosciences union with major regional branches in Africa, central and South America, Asia/Oceania, and North America/Europe, and with major disciplinary and interdisciplinary associations. After convergence, integration, and finally fusion of international geoscientific unions, on the one hand, and convergence or alliance of national and regional geoscience societies, on the other hand, the international geosciences union could then act as a (financially self-maintained) scientific body, coordinating activities of its regional branches and its scientific associations. This union could provide a full spectrum of services and benefits to its members: from scientific meetings and publications to involvement in the initiation, promotion, and implementation of national, regional and international scientific programs, scientific specialized commissions and working groups, and geoscientific services and outreach programs linking science to society and national and international policy. Such an international organization could become a single but powerful voice of Earth and space sciences and promote science to benefit humanity in a more efficient way.

The second scenario is more conservative. International scientific unions as well as national and regional societies of geoscientists would continue their operations reshaping their structure and activities to meet modern scientific challenges. They could establish/strengthen cooperation amongst themselves using a complementary rather than competitive approach. In the long term, this scenario may lead to a fusion (such as in the first scenario).

The third scenario would have a negative impact on international cooperation and development. National and regional societies of geoscientists would continue to enhance their activities and to attract more and more scientists (especially those of younger generations) to membership and to address national and regional policies encouraged by national governments or regional political structures (e.g., the European Union). National scientific institutions or academies provide the funds necessary for adherence to the international Unions. If these bodies in some developed countries were to adopt shortsighted policies by withdrawing from membership of the Unions or reducing the amount of membership dues paid, the international Unions would lose the ability to continue their operations and would cease to exist. The disappearance of international scientific unions would (i) lead to "nationalism" in science (e.g., US, European or Chinese science), which may lead to replacement of "science for peace" by "science for defense", and to significant polarization; (ii) result in the disintegration of many important scientific programs already established; (iii) harm (if not end) new international multidisciplinary programs; and (iv) become a destructive force for the world's scientific development and cooperation, as many developing nations get involved in scientific programs mostly via international programs and through the activities of international scientific unions. Also, climatic and environmental change influences the world globally, and disasters caused by natural hazard events do not respect political borders. We need globally collected and shared data and joint research cooperation efforts to understand, model and forecast these and many other phenomena and their societal impacts. Our global networks of sensors and observatories, remote sensing missions, and international marine cruises to collect data over the oceans, are crucial. Science with borders does not serve anyone well.

These scenarios describe a wide range of possibilities for the future development of IUGG and other international scientific unions, and being extreme case scenarios the first and third scenarios are unlikely to be realized in full.

10.5 Scientific challenges

IUGG will continue to provide balanced, factual, and independent scientific information within its remit of Earth and space sciences. Besides knowledge, which satisfies the curiosity of human beings related to the planet on which they live, and to the Moon, planets, Sun, and stars, which they observe every day, IUGG provides information, understanding, and guidelines on important society-relevant problems to deliver science for the benefit of humanity. Among the problems IUGG has been addressing and will continue to address are: (i) climate variability and the contribution of CO_2 emission to its change to ensure continued habitability of our planet for future generations; (ii) environmental pollution and its reduction in megacities to improve the quality of life; (iii) natural hazards (e.g., hurricanes, floods, earthquakes, landslides) and mitigation/prevention of disasters to save lives and infrastructure; (iv) weather, water, and soil conditions to assist farmers to grow food and provide other indispensable ecosystem services; (v) mineral resources for future generations; (vi) clean water and reduction in contamination to preserve and enhance human and ecosystem health; (vii) space and geodetic measurements for navigation of airplanes and satellites and other applications; and (viii) pollution of oceans and seas, biodiversity and food security. IUGG will continue to increase geoscience literacy through capacity building activities globally and especially in the developing world.

One of current challenges of scientific organizations, including IUGG, is to promote and to strengthen research cooperation fostering development for science policy within a complicated scientific landscape with emerging policy-oriented international programs. Science policy and diplomacy have been always essential components of IUGG activities and should remain in its core activities. Recent examples of science policy and diplomacy work include a synthesis report on science for disaster risk reduction presented at the UN Third World Conference on Disaster Risk Reduction in 2015 (Ismail-Zadeh and Cutter, 2015), a report on future of the ocean submitted to the G7 Science Ministers meeting in 2016 (Williamson et al., 2016), and publications on global change and the future of our planet (Beer et al., 2018), and disaster-related science diplomacy (Kontar et al., 2018).

Adopted by the UN General Assembly in 2015, the 2030 Agenda for Sustainable Development represents a new way of thinking about how better to link issues such as climate change, natural disasters and education. It intertwines social, economic, and environmental targets in 17 Sustainable Development Goals (SDGs; UN, 2015). IUGG has been contributing, and will continue to do so, to many of the SDGs; in particular, IUGG deals with promotion of studies in air pollution (sub-goal 3.9), climate and environmental issues (1.5, 2.5, 3.9, 11.6, and 13.3), hazard and disaster risk (1.5, 2.5, 11.5, 11b, 13.1, and 15.3), education and capacity building (4.7, and 4b), energy (7a), oceans and seas (14.1–14.3, 14a, and 14c), research and innovation (9.5, and 9b), water issues (3.9, 6.3–6.7, 15.1, and 15.3), and the Union continually seeks to improve it gender balance (5.5). All Union Associations, the Union Commissions such as GRC, CCEC, and UCDI, and the IUGG Committee on Capacity Building and Education will contribute to the SDGs mentioned above. For example, the IAMAS Commission on Atmospheric Chemistry and Global Pollution and the IAHS International Commission on Water Quality contribute to sub-goal 3.9 "to reduce the number of deaths and illnesses from [...] air, water [...] pollution and contamination"; the IASPEI-IAVCEI-IAPSO's International Heat Flow and Tsunami Commissions advance knowledge on geothermal energy and tsunami, respectively; and IAPSO and IAHS contribute to issues of the ocean, seas and water (Ismail-Zadeh, 2016).

In 2016, IUGG issued its first Strategic Plan (IUGG-SP, 2016) and its implementation actions until 2023 (IUGG-IA, 2017). Among the important future key actions are to (i) promote IUGG to its constituents, and to geoscientists, policymakers and society in general; (ii) encourage closer cooperation between the IUGG groups and more effective engagement with sister organizations, and other partner agencies; (iii) assist underrepresented geoscientists to more fully participate in international science activities; (iv) strengthen the effectiveness of the Union's Council and the Executive Committee; (v) strengthen the promotion of fundamental research and education in the geosciences; and (vi) encourage more countries to become a member of the Union.

IUGG will maintain and enhance the links between scientists by initiating and developing various scientific, educational and outreach programs and scientific meetings, including the Union general assemblies and Association scientific assemblies, in cooperation with other international and intergovernmental organizations. It will continue to help in setting international geoscientific agendas, policies, recommendations, and guidelines.

IUGG played a significant role in the promotion of Earth and space sciences via international cooperation in the 20th century (the International Geophysical Year is a shining example of such cooperation). And the Union still has the potential to do so in the 21st century by playing an important role in Earth and space sciences, particularly in establishing the terms and conditions for international research cooperation, setting scientific standards and nomenclatures, preparing universal tools, and supporting and promoting excellence, innovation, scientific freedom, inclusivity, diversity, and free access to geophysical data/services and to science education.

11 IUGG leadership

Finally, in this section we highlight the Presidents and Secretaries General, who have contributed significantly to the development of the Union and its Associations at the beginning of the 21st century.

Masaru Kono, President (1999–2003). Masaru Kono (Japan, born in 1939) is a geophysicist, and his research is concerned with the magnetic field of the Earth, in particular, paleomagnetism and dynamo theory. Kono graduated from the University of Tokyo in 1963 and received his PhD from the same university in 1971. From 1968, he worked as Research Associate and then as Associate Professor at the Geophysical Institute of the University of Tokyo. Since 1980, he has held professor's positions at Tokyo Institute of Technology, the University of Tokyo, and Okayama University, until his retirement in 2005. Kono was IAGA Vice President (1991–1995), and then President (1995–1999). He also served as Vice Chair of the IUGG SEDI, as a Member of the Scientific Boards for the International Geoscience Program of UNESCO and IUGS, for the Science Council of Japan, and for the International Ocean Drilling Program. He is Fellow of IUGG, AGU, Japan Geoscience Union, IAGA, and honorary Fellow of the Royal Astronomical Society.

JoAnn Joselyn, Secretary General (1999–2007). JoAnn Joselyn (USA, born in 1943) is an astrogeophysicist who grew up during a period of, and achieved, amazing firsts, when advances in science and space exploration captured the imagination of people around the world. Following an undergraduate degree in applied mathematics at the University of Colorado (CU) at Boulder, she became the first woman to earn a doctoral degree at CU in astrogeophysics, the study of solar–planetary interactions. As a space scientist at the National Oceanic and Atmospheric Administration in Boulder, she showed that ejections of solar wind associated with disappearing solar filaments caused magnetic storms that can disrupt communications, electrical power transmission, space flight, and other emerging technologies. Joselyn became the first woman to be elected IAGA Secretary General (1995), and then the first woman and first American to be elected IUGG Secretary General. She is an IUGG Fellow.

Uri Shamir, President (2003–2007). Uri Shamir (Israel, born in 1936) is a hydrologist. He graduated from the Technion – Israel Institute of Technology in 1962, and received his PhD in 1966 from the Massachusetts Institute of Technology, Cambridge, USA. Since 1979, Shamir has been Professor (Emeritus from 2004) in the Faculty of Civil and Environmental Engineering, and Founding Director (1992–2003) of the Stephen and Nancy Grand Water Research Institute, at the Technion. In 1992 Shamir has been Visiting Professor in various universities and research institutes in the USA and Canada, and was Chairman of the Israeli Association of Hydrology. He served as IAHS President (1991–1995), IUGG Vice President (1995–2003), and a Member of the ICSU Executive Board (2005–2011). He chaired the Technical Advisory Committee of the World Water Assessment Programme (WWAP-TAC), the UN water program led by UNESCO. He is a Fellow of IUGG, AGU, and the American Society of Civil Engineers, and a Foreign Member of the Spanish Academy of Science.

Tom Beer, President (2007–2011). Tom Beer (Australia, born in 1947) is an atmospheric scientist. Beer graduated from the University of Sydney in 1966, and obtained his PhD from the University of Western Ontario in 1971. He led the Climate Research Program of the Centre for Australian Weather and Climate Research, a partnership between the Commonwealth Scientific and Industrial Research Organization (CSIRO) and the Australian Bureau of Meteorology. Beer served IUGG as Bureau Member and Vice President before he was elected President. Beer was a founder of the IUGG GRC in 2000, becoming its first Chair, and of the IUGG CCEC in 2011, also becoming its first Chair. He served on the ICSU Committee for Scientific Planning and Review. He was awarded a Doctor of Science degree by the University of Canterbury in New Zealand. He was elected Fellow of several societies and foreign member of the Hungarian Academy of Sciences.

Harsh Gupta, President (2011–2015). Harsh Gupta (India, born in 1942) is a geoscientist and seismologist. He received his BSc (Hons) and MSc degrees from the Indian School of Mines, Dhanbad, before he obtained his PhD degree from the Indian Institute of Technology, Roorkee. He worked at the University of Texas at Dallas (USA) before he returned to India and became Director of the Centre for Earth Science Studies, Thiruvananthapuram, in 1982. He held positions of Vice Chancellor of Cochin University of Science and Technology, Director of the National Geophysical Research Institute (NGRI) in Hyderabad, and Secretary at the Department of Ocean Development of the Government of India. At present, Gupta is a Raja Ramanna Fellow at NGRI. Before Gupta was elected IUGG President, he served the IUGG Bureau as Member (1999–2007) and Vice President (2007–2011). He served on the ICSU Committee for Scientific Planning and Review. Gupta held leadership roles in several national and international scientific organizations. He is an AGU Fellow and a member of several national academies.

Michael Sideris, President (2015–2019). Michael Sideris (Canada, born in 1958 in Greece) is a geodesist with expertise in the fields of satellite Earth observation. He received his Diploma (Hons) from the National Technical University of Athens, Greece, in 1981, and M.Sc. (1984) and PhD (1987) from the University of Calgary, Canada. Since 1988 Sideris been working in the Department of Geomatics Engineering at the University of Calgary, where he is currently Professor and Associate Head (Graduate Studies). He has also served the university as Associate Dean of the Faculty of Graduate Studies and Associate Dean of Research of the Schulich School of Engineering. He has been visiting Professor at several Asian, Australian, European, and South American universities/institutes. He was IAG Vice President (2003–2007) and President (2007–2011), and IUGG Vice President (2011–2015). Since 2016 Sideris has been serving on the GEO Program Board. He is an Alexander von Humboldt International Research Fellow, IAG Fellow, and IAG Honorary President.

Kathryn Whaler, Vice President (2015–2019). Kathryn Whaler (UK, born in 1956) is a geophysicist with expertise in the fields of core dynamics, crustal magnetization, magnetotellurics, and geomagnetic observations. She received a BSc in Mathematical Physics from the University of Sussex in 1977 and a PhD from the University of Cambridge in 1981. Whaler joined the University of Leeds in 1983 as a lecturer, and in 1994, she moved to the University of Edinburgh to take up the Chair of Geophysics. She was the President of the Royal Astronomical Society (2004–2006). She served IAGA as Executive Committee Member (2003–2007), Vice President (2007–2011), and President (2011–2015) before she was elected IUGG Vice President (2015–2019). She has visited the NASA's Goddard Space Flight Center, Harvard University, the University of California at San Diego (as Green Scholar), Victoria University of Wellington, and Göttingen University (as Gauss Professor). Whaler is Fellow of AGU, the Institute of Physics, and the Royal Society of Edinburgh.

Alik Ismail-Zadeh, Secretary General (2007–2019). Alik Ismail-Zadeh (Germany/Russia, born 1961 in Azerbaijan) is a mathematical geophysicist, graduating from Baku State University (mathematics) and Lomonosov Moscow State University (physics) before being awarded PhD and DSc degrees in geophysics from the Russian Academy of Sciences (RAS). He has been Chief Scientist/Research Professor of RAS in Moscow since 1998, and Senior Scientist at the Karlsruhe Institute of Technology, Germany since 2001. He was a visiting professor at several universities, including in China, France, Japan, Sweden, UK, and USA. He is a co-founder of the IUGG GRC (Chair, 2004–2007) and a co-founder of the AGU Natural Hazard Section (Chair, 2009–2012). He has served or is serving on governing or advisory committees of international and intergovernmental organizations and programs, including AGU, CTBTO, UNISDR, and UNESCO. He was elected the first ISC Secretary (2018–2021). He is an elected member of Academia Europaea and an honorary Fellow of the Royal Astronomical Society.

12 Conclusions

Since its formation in 1919, IUGG has been committed to dedicated to initiating, promoting and coordinating international scientific studies and observations of the Earth and its environment in space. Today, as a vibrant modern scientific union of nations and individual scientists from all over the world, the Union is proud to promote research, science education, and capacity building via international cooperation, linking scientific knowledge to societal needs, and working toward a sustainable Earth (Ismail-Zadeh, 2016).

IUGG's centennial history (Appendix B) illustrates how hundreds of thousands of Earth and space scientists have developed and cooperated in international research to benefit society and promoted fundamental science as well as science for society. The Union encourages the application of this knowledge to societal needs, such as the mitigation of impacts from natural hazard events, the sustainable use of energy and mineral resources, and environmental preservation (Ismail-Zadeh and Beer, 2009). Particularly, IUGG responded vigorously to the challenges associated with climatic and environmental changes, disasters, water issues and many others, promoting research and scientific cooperation. The Union has played an important regulatory role in geodetic and geophysical sciences, particularly in establishing the terms and conditions for international research cooperation, setting scientific standards and nomenclatures, preparing universal tools and data products, among other aspects. IUGG brought state-of-the-art science to less affluent countries through capacity building and science education. The Union links scientists via its scientific, educational and outreach programs to programs of intergovernmental organizations and assists in establishing international scientific agendas, policies, recommendations, and guidelines (Ismail-Zadeh, 2016).

Since the beginning of the 21st century, IUGG has been involved in the process of reshaping its structure and activities to meet its scientific and organizational needs (see Ismail-Zadeh, 2016, for more details). The most notable of these changes are the following.

- To make the Union more vibrant in terms of decision making, the Council has become a continuously operating body.
- Scientists from any country are now eligible to hold most positions within the IUGG family with a few exceptions, which can only be held by scientists from Member Countries.
- Four standing Union Committees on Membership Issues, Capacity Building and Education, Honor and Recognition, and Visioning have been formed to help the Union reshape its membership structure and science education programs, establish Union awards and medals, and develop IUGG strategic planning.
- Affiliate membership of IUGG was established to strengthen cooperation with geoscientific organizations worldwide.
- Three Union Commissions – Data and Information, Climatic and Environmental Change, and Planetary Sciences – as well as the Union Working Group on History have been established to coordinate activities across IUGG associations and other international organizations on relevant scientific topics.
- IUGG established a new Grants Program to support interdisciplinary projects, which will explore new scientific ideas and develop future international initiatives.
- IUGG renewed its publication policy, and agreed to produce a series of works entitled "Special Publication of the IUGG" published by Cambridge University Press.
- The Union put forward a new initiative to enhance geophysical and geodetic science education centered on less affluent areas of the world and developed a fruitful cooperation with the Abdus Salam International Centre for Theoretical Physics.

– IUGG established the honors program to recognize Earth and space scientists for their outstanding contributions to geodesy and geophysics and for unselfish international scientific cooperation.

Changes such as these enable the Union to do its best work in support of its mission, which is to continue to advance, strengthen and promote Earth and space sciences for the benefit of humanity, through international research cooperation and education, and to communicate the knowledge to governments and policy-makers (IUGG-SP, 2016). The application of Earth and space sciences to societal needs requires coordinated efforts between IUGG and other scientific bodies and stakeholders, including professional societies and intergovernmental organizations. IUGG will continue to evolve throughout the coming decades in step with the changing world of science and its international organizations, responding to the challenging problems of society.

Data availability. The paper is based on (i) published documents (see a list of references) as well as (ii) IUGG Archive documents. The original hard-copy documents of IUGG are deposited in the Niels Bohr Library and Archives of the American Institute of Physics (AIP, 2019). The documents are accessible only in the library with the permission of the IUGG Secretary General.

Appendix A

Table A1. Member Adhering Bodies of IUGG (1919–2019).

No.	Members	Dates of admission and termination	No.	Members	Dates of admission and termination
1	Albania	1997	51	Korea	1960
2	Algeria	1971–2006, 2018	52	Korea Dem. Rep.	1967–2000
3	Argentina	1927	53	Lebanon	1967–2003
4	Armenia	2000	54	Libya	1979–1996
5	Australia	1919	55	Luxembourg	1971
6	Austria	1948	56	Macedonia, F. Y. R.	1995–2001, 2010
7	Azerbaijan	2010	57	Madagascar	1967–1995
8	Belgium	1919	58	Malaysia	1967–2002
9	Bolivia	1960–2000, 2006	59	Mauritius	2003
10	Bosnia and Herzegovina	2003	60	Mexico	1922
11	Brazil	1922	61	Monaco	1967–2013
12	Bulgaria	1930	62	Mongolia	1995–2001
13	Burundi	1987–1995	63	Morocco	1924
14	Canada	1919	64	Mozambique	1983
15	Chile	1924	65	Myanmar (Burma)	1957–2003
16	China – CAST	1977	66	Nepal	1975–1987
17	China – Acad. Sci. in Taipei	1995	67	Netherlands	1925
18	Colombia	1938–1971, 2000	68	New Zealand	1927
19	Congo Dem. Rep.[a]	1991–1997, 2004	69	Nicaragua	2014
20	Costa Rica	2010	70	Nigeria	1971
21	Croatia	1992	71	Norway	1923
22	Cuba	1960–1996	72	Pakistan	1952
23	Czech Rep.	1993	73	Peru	1925–1979, 2000
24	Denmark	1923	74	Philippines	1951–2015
25	Dominican Rep.	1957–1971	75	Poland	1924
26	Egypt	1924	76	Portugal	1919
27	Estonia	1991	77	Romania	1930
28	Ethiopia	1952–2000	78	Russia[b]	1954
29	Finland	1927	79	Saudi Arabia	1971–2001, 2012
30	France	1919	80	Senegal	1960–1995
31	Georgia	2009	81	Serbia[c]	1996–2006, 2018
32	Germany	1951	82	Sierra Leone	1967–1983
33	Ghana	1957–1987, 2006	83	Slovak Rep.	1993
34	Greece	1922–2003, 2008	84	Slovenia	1994
35	Guatemala	1957–2000	85	South Africa	1924
36	Guinea	1987–1995	86	Spain	1922
37	Haiti	1956–1971	87	Sudan	1955–2000
38	Hungary	1930	88	Sweden	1923
39	Iceland	1967	89	Switzerland	1923
40	India	1947	90	Syria	1948–1995
41	Indonesia	1951	91	Tanzania	1975–2000
42	Iran	1957	92	Thailand	1923
43	Iraq	1983–1996	93	Tunisia	1927–2001
44	Ireland	1946	94	Turkey	1949
45	Israel	1951	95	UK	1919
46	Italy	1919	96	Uruguay	1924–2000, 2019
47	Ivory Coast	1975–1996	97	USA	1919
48	Japan	1919	98	Venezuela	1975–2008
49	Jordan	1979	99	Vietnam	1931
50	Kenya	1975–1997	100	Zimbabwe	1967–2000

[a] Admission in 1991 under the name Zaire; membership terminated in 1997. [b] Admission in 1954 under the name of the USSR; Russia since 1992. [c] Admission in 1996 under the name of the Fed. Rep. of Yugoslavia which was changed to Serbia and Montenegro in 2003, and changed to Serbia in 2018.

Appendix B

Table B1. IUGG timeline (1919–2019).

Year	Activity	Place
1919	IUGG was founded with six Sections (Geodesy, Terrestrial Magnetism and Electricity, Meteorology, Physical Oceanography, Seismology, and Volcanology)	Brussels, Belgium
1922	Seventh Section, Scientific Hydrology, was added	Rome, Italy
1932/1933	The Second International Polar Year	
1933	Sections were renamed International Associations	Lisbon, Portugal
1946	Extraordinary General Assembly to reconstitute IUGG following WWII	Cambridge, UK
1946	IUGG and U.N. Education, Scientific and Cultural Organization (UNESCO) signed a working agreement	Paris, France
1951	The International Association (IA) of Seismology became the IA of Seismology and Physics of the Earth's Interior (IASPEI)	Brussels, Belgium
1952	First issue of the IUGG Bulletin, which became the IUGG Chronicle (ceased in 1995)	
1954	IUGG and the World Meteorological Organization (WMO) signed a working agreement	Geneva, Switzerland
1957/1958	The International Geophysical Year (IGY)	
1957	The IA for Terrestrial Magnetism and Electricity became the IA for Geomagnetism and Aeronomy (IAGA)	Toronto, Canada
1960	Cooperation with the Intergovernmental Oceanographic Commission of UNESCO started	Paris, France
1967	First use of the present day IUGG logo	Zurich, Switzerland
1967	The IA of Volcanology became the IA of Volcanology and Chemistry of the Earth's Interior (IAVCEI)	Zurich, Switzerland
1967	The IA of Physical Oceanography became the IA for the Physical Sciences of the Ocean (IAPSO)	Zurich, Switzerland
1971	The IA of Scientific Hydrology became the IA of Hydrological Sciences (IAHS)	Moscow, USSR (now Russia)
1971	The Inter-Association Committee on Mathematical Geophysics (now the Union Commission on Mathematical Geophysics – CMG) was established	Moscow, USSR (now Russia)
1975	Cooperation with the International Hydrological Program of UNESCO started	Paris, France
1987	Union Committee on the Study of the Earth's Deep Interior (now the Union Commission SEDI) was established	Vancouver, Canada
1988	The first International Terrestrial Reference Frame is released by the IAG	
1991	The International Lithosphere Program becomes an IUGS/IUGG inter-Union body	Vienna, Austria
1995	The International Association of Meteorology and Atmospheric Physics (IAMAP) becomes the IA of Meteorology and Atmospheric Sciences (IAMAS)	Boulder, USA
1998	IUGG website established	

Table B1. Continued.

Year	Activity	Place
2000	Union Commission on Geophysical Risk and Sustainability (GRC) was established	
2001	IUGG monthly E-Journal established	
2003	Early Career Scientist Union Symposium series was established	Sapporo, Japan
2004	ICSU GeoUnions consortium was established	Paris, France
2007	International Association for Cryospheric Sciences was established	Perugia, Italy
2008	The IUGG Grants Program was established	
2007/2008	The Electronic Geophysical Year (eGY) The International Heliophysical Year (IHY) The International Year of Planet Earth (IYPE) The International Polar Year (IPY)	
2008	The Union Commission for Data and Information (UCDI) was established	
2011	IUGG and the Abdus Salam International Centre for Theoretical Physics (ICTP) agreed to develop a joint geophysical and geodetic science education program	Trieste, Italy
2011	Affiliate Membership and Honorary Membership were established	Melbourne, Australia
2012	The Union Commission on Climatic and Environmental Change (CCEC) was established	
2012	The Working Group on History was established	
2012	IUGG signed a Memorandum of Agreement with the Cambridge University Press to publish a series of works entitled “Special Publications of the IUGG”	
2013	IUGG became a Participating Organization of the Group on Earth Observations (GEO)	Geneva, Switzerland
2015	First IUGG Awards (Gold Medal, Silver Medal, IUGG Fellows, and Early Career Scientist Award) presented	Prague, Czech Republic
2015	The Union Commission on Planetary Sciences (UCPS) was established	
2016	New Association logos designed and approved	
2016	Strategic Plan 2016–2023 and its Implementation Plan were adopted	
2017	IUGG became an Observer Organization of the Intergovernmental Panel on Climate Change (IPCC)	Geneva, Switzerland
2019	IUGG Centennial	Montreal, Canada

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Open Access History of Geo- and Space Sciences

IACS: past, present, and future of the International Association of Cryospheric Sciences

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Abstract. The International Association of Cryospheric Sciences (IACS) became the eighth and most recent association of IUGG at the general assembly in Perugia, Italy, in July 2007. IACS was launched in recognition of the importance of the cryosphere within the Earth system, particularly at a time of significant global change. It was the first new association of the union to be formed in over 80 years and IACS celebrated its 10th anniversary only a year before the IUGG centennial. The forbearers of IACS, however, stretch back even further than IUGG, starting with the formation of the Commission Internationale des Glaciers (CIG) by the International Geological Congress in 1894. Here we record the history of the transition from CIG to IACS, the scientific objectives that drove activities and changes, and some of the key events and individuals involved.

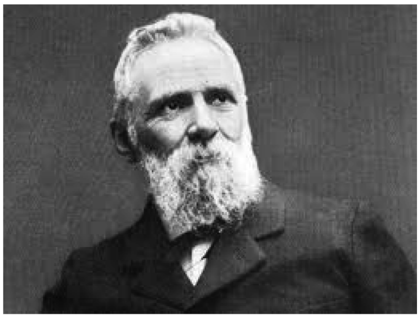
1 Introduction: what is cryospheric science?

The term "cryosphere" traces its origins to the Greek word *kryos*, meaning frost or icy cold. It collectively describes the components of the Earth's surface that contain ice, including snow, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost and seasonally frozen ground. Permafrost, however, can be "dry" and therefore the cryosphere also includes any natural material in frozen form. The origin of the term can be traced to the Polish scientist A. B. Dobrowolski in his 1923 book on *The Natural History of Ice* (Barry et al., 2011).

The cryosphere is an integral part of the Earth system with important linkages and feedbacks generated through its influence on surface energy and moisture fluxes, clouds, precipitation, hydrology, and atmospheric and oceanic circulation. It plays a significant role in global climate, in climate model response to global change and as an indicator of change in the climate system (e.g. Allison et al., 2001). Within the Global Climate Observing System (GCOS; https://public.wmo.int/en/programmes/global-climate-observing-system, last access: 12 December 2018), variables from the cryosphere are recognized as essential climate variables (ECVs) that critically contribute to the characterization of Earth's climate (Bojinski et al., 2014).

Cryospheric science is a rapidly expanding and increasingly diverse discipline. There is clear recognition that the cryosphere is a critical part of the total Earth system, particularly for climate and climate change. So cryospheric science must include the interactions with the other Earth "spheres". For example, some of the climate-system models in Phase 6 of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP6) include specific ice sheet models; and an Earth System Model-Snow Model Intercomparison Project (ESM-SnowMIP) is a targeted activity of the WCRP Climate and Cryosphere (CliC) project. But cryospheric science also considers glacier and ice sheet modelling; sea ice dynamics and ocean–ice–atmosphere interaction; ice mechanics and rheology; and

Box 1 François-Alphonse Forel (1841–1912)
President, Commission Internationale des Glaciers (1894–1897)



Forel was a Swiss physician and scientist, and is considered the founder of limnology, the study of lakes. He lectured in physiology and anatomy at the University of Lausanne, but also spent a lifetime studying the biology, chemistry, water circulation, sedimentation, and their interactions, in Lake Geneva near which he lived. He is credited with the discovery of density currents in alpine lakes, helped explain the mechanism of seiches, and introduced the term "limnology".

Forel was fascinated by natural science, writing to his grandchildren "Naturaliste de coeur et de profession, j'ai dévoué ma vie à la recherche de la vérité dans les sciences naturelles; je crois l'avoir atteinte quelquefois" (Forel, 2012), and he also investigated earthquakes and glaciers. The first 32 annual reports on the variations of Swiss glaciers, which commenced in 1881 and which continue today, were (co-)edited by Forel.

Box 1.

atmosphere–snow interaction, including chemistry, snow redistribution by wind, remote sensing and geophysical methods; and much more.

Cryospheric science also includes the applied science of technical and environmental problems, such as hazards in mountains and glacierized regions, particularly avalanches and glacier lake outburst floods (GLOFs); construction on, and transport over, snow, ice and permafrost surfaces; shipping in ice-covered oceans, lakes and rivers; icing of ships, aircraft and structures; and recreational and tourism activities in snow-covered regions. It also includes studies of the cryosphere elsewhere in the solar system.

In this account of the development of international cryospheric institutions, we draw extensively on prior histories of the Commission Internationale des Glaciers (CIG) and its successor, the International Commission of Ice and Snow (Radok, 1997) and on the transition into the independent association, the International Association of Cryospheric Sciences (IACS; Jones, 2008).

2 The Commission Internationale des Glaciers (CIG) (1894–1927)

Systematic collection of information about ongoing glacier changes was initiated on 31 August 1894 when the Council of the sixth International Geological Congress, meeting in Zurich, Switzerland, agreed to create the Commission Internationale des Glaciers.

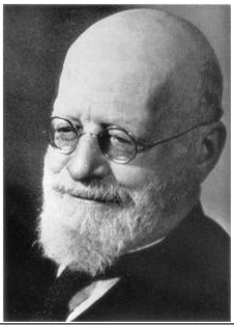
Earlier, in 1879, François-Alphonse Forel (Box 1) had started annual observations of the variation of glacier fronts in the Swiss canton of Valais. He wished to determine if there was a link between these and changes to the level of Lake Geneva (Lac Léman) and subsequent flooding. Noting that there was no theory to explain glacier variations, he motivated systematic observations in other countries, including France, where a similar network was established by Prince Roland Bonaparte, who had explored and described glaciers in the French Alps and the Pyrenees in the 1870s and 1880s. But it was Captain Marshall Hall of the Wiltshire Militia, a Fellow of the Geological Society of London and who had worked with Forel in the Swiss Alps in the 1880s who, on behalf of the three, presented the formal proposal for the creation of the CIG to the International Geological Congress Council.

Hall's 1894 letter to the International Geological Congress noted that, by this time, several (mostly European) countries compiled reports on glacier frontal variations, although there was little information on glaciers in other regions such as the Arctic and Antarctic, Scandinavia, Iceland, Greenland, the Himalayas, America, and New Zealand. He suggested that the results obtained in each country would be more useful for investigation of the influence of climate on the variations in the size of glaciers if combined into a single annual report (which could also encompass meteorological data). He proposed the creation of a commission, composed of one or more members from each country, who would select a national "recorder" to report each year on glacier fluctuations to the president of the commission. The president would assemble these as a combined report in a single language (French). While each country would be independent in the study of its glaciers, the commission would indicate observational guidelines to make the national reports comparable with one another. Forel provided the theoretical and conceptual framework for the commission and became its first president. Prince Bonaparte provided funds for the work of the commission.

A preliminary report by Forel (1895) contained technical concepts and general principles for the CIG. In this he highlighted the importance of glacier observations that would support development of a theory of the relationship between

Box 2 Sebastian Finsterwalder (1862–1951)

President, Commission Internationale des Glaciers (1900–1903)



Finsterwalder, born in Bavaria, was a mathematician, surveyor, glaciologist and keen mountaineer. He was professor in the Department of Analytical Geometry, Differential and Integral Calculus at the Technical University of Munich from 1891. He pioneered precision mapping of glaciers in the Austrian Alps and mathematical modelling of glaciers. Finsterwalder is considered the father of glacier photogrammetry for his pioneering use of repeat photography as a temporal surveying instrument in measurement of the geology and structure of the Alps and of glacier flow.

His son, Richard, was the fourth president of the International Commission on Snow and Ice (Section 4) from 1956 to 1960.

Box 2.

glacier variations and meteorological conditions. But he also recognized that the individuality of different regions required that the collaborators should be free to determine the glacier monitoring tasks needed to address the fundamental scientific interests of the CIG. The first CIG report on observations of glacier variations made in 1895 in various parts of the world was published by Forel and Du Pasquier (1896). President Forel also reported to the next International Geological Congress in St Petersburg in 1897 at the end of his 3-year term, addressing the basic concepts and methods used in recording glacier variations.

The five CIG presidents that followed Forel reported to successive International Geological Congresses up to 1913, although each outgoing president's report differed widely in content depending on their field of expertise. For example, at the 1903 Vienna Congress the third president, Sebastian Finsterwalder (Box 2), outlined a mathematical formulation for the changes to glacier size and shape in response to changes in snow accumulation and ablation. And at the 1906 Congress in Mexico City the fourth president, Harry Fielding, Professor of Geology at The Johns Hopkins University, Baltimore, reported the first data from Antarctica and compared different national formulations of data for the CIG. Altogether, the preliminary report plus nineteen reports on annual observations were published by successive CIG presidents. The CIG reports on glacier variations ended at the outbreak of the First World War.

The final CIG president, Axel Hamberg, Professor of Geography at Uppsala University, Sweden, was elected by postal vote as only one CIG member was able to travel to the 1913 Toronto Congress. Paul-Louis Mercanton (Switzerland) became secretary of the commission. The activities of the CIG then stalled with the outbreak of the First World War, although Hamberg and Mercanton remained as nominal officers until 1927. A chronology of all seven CIG presidents and the secretaries is available at https://wgms.ch/about_history/ (last access: 12 December 2018).

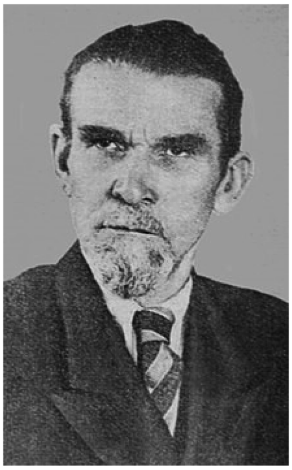
3 The International Commission of Ice and Snow (ICSI/IASH): first period (1927–1965)

On 28 July 1919 in Brussels, nine of the founding national members of the International Research Council (IRC) established the International Union of Geodesy and Geophysics (IUGG) (Union Géodésique et Géophysique Internationale, UGGI). The IRC initially specifically excluded Germany and the other "central powers" of the war from joining it or its various disciplinary unions, and it was not until 1926 that this restriction was revoked. In 1922, in Rome, a Section d'Hydrologie Scientifique (SHS) was launched within IUGG. This was, in 1930, renamed as the International Association of Scientific Hydrology (IASH).

Establishment of a Commission de Glaciologie[1] as one of four commissions within SHS had been proposed in Rome in 1922. But Hamberg also proposed to seek re-establishment of CIG at the next International Geological Congress. So, in Madrid in 1924, Mercanton persuaded SHS to postpone the decision to establish a Commission de Glaciologie until 1927 to avoid any duplication. Hamberg's 1926 appeal to the International Geological Congress Bureau for reconstitution of the CIG was unsuccessful (Baird, 1958). Reconstituting a glacier group within IUGG became increasingly attractive after the IRC statutes were amended to allow the former "central power" nations to join and also since IUGG could provide some funding to support activities, whereas the International Geological Congress did not. So, at the September 1926 meeting of the SHS Executive Committee (EC) in Geneva, Mercanton proposed to formally disband CIG and replace it with the SHS Commission de Glaciologie. This proposal was agreed to, even before the general assembly. The Commission de Glaciologie was then formally approved at the 1927 Prague IUGG General Assembly, after 16 of 18

[1] Commission de Glaciologie, Commission Glaciologique, Commission pour la Glaciologie and Commission des Glaciers were used interchangeably in the SHS and IASH Bulletins Nos. 1 to 20 from 1924 to 1933.

Box 3 Antoni Bolesław Dobrowolski (1872–1954)
Vice president IASH Commission des Glaciers (1933–36)
Vice president, Commission des Neiges et Glace (1936–39)



Dobrowolski was born in Poland and, as a student, was involved in an illegal political organization seeking independence from the Russian Empire. He was sentenced to 3 years imprisonment in the Caucasus, but escaped after 2 years and went on to study physics and biology in Switzerland and Belgium. While still a student, he participated in the Belgian Antarctic Expedition to the Bellingshausen Sea (1897–1899), becoming the assistant meteorologist to the chief physical scientist, Henryk Arctowski.

Dobrowolski wrote what is considered the first modern textbook on glaciology, in part based on his Antarctic observations. In *The natural history of ice*, written in Polish and published in 1923, Dobrowolski defines the cryosphere and presents a comprehensive account of all forms of snow and ice – in the atmosphere, on land and water, and in the ground. He promoted the development of many aspects of geophysics in Poland and was patron of Polish participation in the Second International Polar Year (1932–1933) and subsequent Arctic expeditions.

Dobrowolski was a staunch advocate, against opposition from members of the Commission des Neiges (Radok, 1997), for bringing all forms of ice and snow science under one "cryospheric" umbrella. His concept was ultimately realised with the formation, in 2007, of the IACS. Barry et al. (2011) give a fuller history of Dobrowolski and his scientific contributions.

Box 3.

CIG members agreed to dissolve their commission. Although Hamberg had initially wanted to resign, he was persuaded by other members of the CIG to remain as president of the SHS commission. Mercanton became secretary and Charles Rabot (France) was elected vice president. All three had been previously involved in the pre-war CIG, although that had not been active for 13 years.

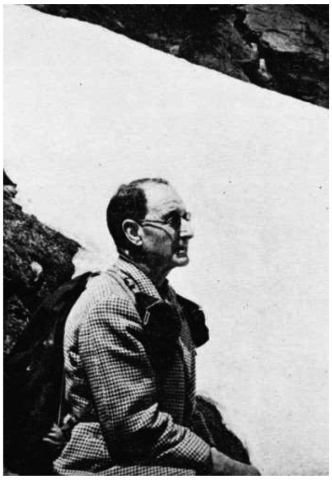
Hamberg published articles on the "fate" of the CIG and guidelines for the measurement of glacier fluctuations (Hamberg 1930a, b). The new group also published an update of glacier fluctuations spanning the gap since the start of the war (Hamberg et al., 1930). Hamberg then resigned as president at the 1930 general assembly of IUGG.

A decision to establish a Commission des Neiges was made at the 1933 general assembly. The first president, J. E. Church (USA), had previously established a similar snow commission within the American Geophysical Union, which was then the American National Committee of IUGG. Although Mercanton had initially wanted to limit the scope of the Commission des Neiges to snow hydrology, by 1936 it was considering all fields of glaciology not covered by its sister commission. The next assembly (Edinburgh, 1936) included a joint symposium of the two commissions. This was strongly supported, with 80 papers contributed to a very large volume of the *Red Book* series (No. 23, with a high publication cost for IASH). It included a paper by A. B. Dobrowolski (Box 3) proposing creation of a single "Association of Cryology" within IUGG. Although this was rejected in 1939 (Washington), and not fully accepted for more than another 70 years, the 1939 general assembly did agree to merge the two committees into a single Commission des Neiges et des Glaciers, with J. E. Church as president. Church noted that the original CIG purpose had broadened to encompass all aspects of the modern science of snow and ice "with its multiple relationships and human services".

Activities then paused until the first post-WWII general assembly in Oslo in 1948. Here the Commission des Neiges et des Glaciers was renamed as the International Commission on Snow and Ice (ICSI), a name and general function it was to retain for more than 50 years. The first ICSI president was Hans W. Ahlmann (1948–1951; Sweden). He had extensively investigated the glaciers surrounding the North Atlantic (including Norway, Sweden, Iceland, Greenland and Svalbard) and later became Sweden's ambassador to Norway (1950–1956) and president of the International Geographical Union (1956–1960).

By this time, the ICSI was forging a network of glaciologists worldwide. For example, the second president, Gerald Seligman (Box 4), was also the founder of the International Glaciological Society (IGS) and the *Journal of Glaciology*. Many in this network became leading figures in the then incipient international polar expeditions. The foundation ICSI president, Ahlmann, was one of the initiators of the first of these, the Maudheim expedition to Antarctica (1949–1952), which became a prelude to the International Geophysical Year (IGY; 1957/1958). And the third ICSI president, Robert

Box 4 Gerald Seligman (1886–1973)
President, International Commission on Snow and Ice (1951–1954)



Gerald Seligman was born in London and from an early age spent holidays in the Alps or in Norway touring the mountains on ski. His interest in snow gradually developed from that of a skier and alpinist to a scientific basis. During a year at the Scott Polar Research Institute in Cambridge, he wrote his classic 1936 book on snow structure and ski fields and organized several field studies of the metamorphosis of snow to glacier ice on the Jungfraujoch.

In 1936, at the urging of J.E. Church who was then president of the IASH Commission des Neiges, Seligman formed the Association for the study of Snow and Ice, which after the war was renamed the British Glaciological Society and eventually, in 1962, the International Glaciological Society. He founded the Journal of Glaciology, the first edition of which was published in 1947, "to publish articles on all aspects of snow and ice research from the purely scientific to the essentially practical". He was editor of the Journal of Glaciology from 1947 to 1968.

Box 4.

Haefeli (1954–1957; Switzerland), was also the first president of the committee directing the Expédition Glaciologique Internationale au Groenland (EGIG; 1957–1960).

A major function of ICSI throughout this period was organization of snow- and ice-related symposia within the 4-yearly IUGG general assemblies, and to publish the proceedings of those in the IASH *Red Book* series, commencing with the 1936 Edinburgh joint Snow and Ice Symposium (No. 23, 1939) (http://www.cryosphericsciences.org/publications.html, last access: 12 December 2018). From 1958 this included specialized snow and ice symposia held between the IUGG assemblies, commencing with a symposium in Chamonix on Dynamics of Glacier Movement. Planning for, and results from, the IGY dominated much of the discussions of ICSI at its Rome (1954), Toronto (1957), and especially Helsinki (1960) assemblies. In 1958, the USSR National Committee for IUGG proposed the formation of a separate snow and ice association, noting especially the contributions and advances made during IGY and the climate links of snow and ice. This proposal was not, however, accepted.

4 The International Commission of Ice and Snow (ICSI/IAHS): second period (1965–2004)

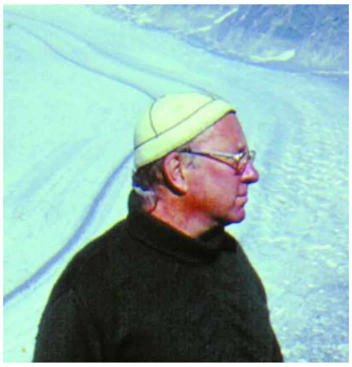
By the mid-1960s, ICSI/IAHS[2] had become organized into four divisions dealing with glaciers and ice sheets; seasonal snow cover and avalanches; sea, lake and river ice; and ground ice.

[2]In 1971, the International Association of Scientific Hydrology was renamed the International Association of Hydrological Sciences (IAHS).

The UNESCO-sponsored International Hydrological Decade (IHD; 1965–1974) provided a major incentive for world-wide hydrological process-oriented investigations and mapping of the water reserves in glaciers and permanent snow fields (Hoinkes, 1968). ICSI established close links with UNESCO and took a lead role in IHD. ICSI presidents Herfried Hoinkes (1963–1967; Austria) and Mark Meier (1967–1971; USA; Box 5) designed and encouraged the snow and ice programs of IHD/IHP, which were then implemented on a national basis. Of particular significance was the program of "Combined Heat, Ice and Water Balances at Selected Glacier Basins". A number of glaciers were selected to represent all major climatic conditions, and standard measurements which could be compared with one another were undertaken for the duration of IHD. The IHD mass balance glossary (ICSI, 1969) and measurement guidelines (UNESCO/IASH 1970, 1973) established standards for harmonizing the monitoring and provided guidelines to create glacier inventories, establishing a glacier coding that is related to hydrologic watersheds. Also, building on the snow expertise of ICSI, a guide for measurement, compilation and assemblage of data for the seasonal snow cover was issued (UNESCO/IASH/WMO, 1970). The International Hydrological Program (IHP) was established as a successor to IHD and is still an active UNESCO program.

As president from 1975 to 1979, Uwe Radok (Australia; Box 6), focused ICSI priority on the role of ice and snow in the climate system, with this leading to the ICSI-sponsored Symposium on Sea Level, Ice and Climate Change at the 1979 general assembly of the IUGG in Canberra. Other symposia on snow and ice science, both as part of IUGG assemblies and during intervening years, continued to be organized by ICSI with proceedings published in the IAHS *Red*

Box 5 Mark F. Meier (1925–2012)
President, International Commission on Snow and Ice (1967–1971)
President, International Association of Hydrological Science (1979–1983)



Mark Meier completed a PhD in 1957 on the dynamics of the Saskatchewan Glacier and became chief of the new Project Office-Glaciology of the US Geological Survey in 1956. He remained there until 1985 when he became Director of the Institute of Arctic and Alpine Research at the University of Colorado.

Mark played a lead role in developing the snow and ice programs of the IHD and is widely considered a forerunner in quantifying the contribution of melting glaciers to rising sea level. He was awarded the 1999 UNESCO/WMO/IAHS International Hydrology Prize for his contribution to the role of glaciers and ice sheets in global hydrology.

Mark was, however, also a strong advocate for the study of ice and snow as part of the total Earth system, rather than limiting the role of the ICSI primarily to hydrology.

Box 5.

Book series. These included a broad range of cryospheric topics such as glacier fluctuation, snow physics and chemistry, avalanches, Antarctic glaciology, glacier hydrology, and snow processes.

The concept of a separate association for cryology, first proposed by Dobrowolski in 1936 and with a widened range of scientific interest beyond the hydrological focus of IAHS, resurfaced throughout this period. For example, President Louis Lliboutry (1983–1987; France) was concerned that many glaciologists were not attracted to ICSI sessions, which were part of IAHS assemblies. And Mark Meier, during a 1994 keynote speech on the centenary of the formation of CIG, emphasized that a primary focus on hydrology was contrary to the role that snow and ice play in the dynamics of the atmosphere, the surface of the land, the oceans, the solid Earth itself and the biosphere (Jones, 2008).

Throughout this period, key advances were also made in small Working Groups (WGs) that were commissioned and supported by ICSI. These included WGs on large-scale effects of seasonal snow cover, problems of snow and ice hydrology in glacierized regions, and remote sensing of ice and snow. Two innovative WGs, SnowMIP1 and SnowMIP2, comprehensively undertook, for the first time, snow model intercomparison projects. SnowMIP1 compared 23 models using observed meteorological parameters from two alpine sites and focused on the validation of snow energy-budget simulations (Etchevers et al., 2004). SnowMIP2 continued the studies and was also adopted as an activity of the WCRP Global Energy and Water Exchanges (GEWEX) Land Atmosphere System Study (GLASS) and the WCRP CliC project (Essery et al., 2009). Also important were training programmes and technology transfer to less-developed countries, such as the ICSI/UNESCO snow and avalanche programmes in 1981 (Islamabad, Pakistan), 1983 (Kathmandu, Nepal) and 1987 (Manali, India).

In 1995, Liz Morris (Box 7), became the first woman president of ICSI, and the first person to serve two terms in this position (1995–2001).

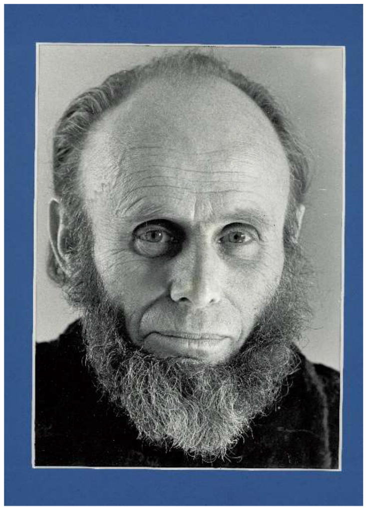
5 From ICSI via UCCS to IACS

It was Liz Morris who initiated and H. Gerald (Gerry) Jones (president-elect, 1999–2001, Box 8) who coordinated the first steps in the successful transformation of the ICSI into the IUGG Association of Cryospheric Sciences (IACS). A discussion paper, concluding that the best option for representing all cryospheric fields would be an independent association within IUGG, was presented to, and accepted by, the ICSI Bureau at the Sixth Scientific Assembly of IAHS at Maastricht in 2001. This was also presented for consideration to the ICSI plenary and to the president of the IAHS.

Liz Morris, Gerry Jones and Georg Kaser (1999–2003 secretary of ICSI) then drafted a position paper for submission at the 2003 Sapporo general assembly, proposing that the IUGG approve and implement a new International Association for Cryospheric Sciences (IACS) and recommending the necessary steps for this. The position paper was developed in consultation with other snow and ice scientific bodies and with assistance from other ICSI officers. In February 2003 it received, through the office of the secretary general Pierre Hubert, support from IAHS. The proposal was formally submitted to IAHS and the IUGG Executive Committee (EC) at Sapporo in March 2003. President Gerry Jones, supported by the new president-elect Georg Kaser, made a strong case for IACS. The IUGG EC responded positively, although it requested that more details on the proposal should be submitted to its next meeting and recommended that an interim inter-

Box 6 Uwe Radok (1916–2009)

President, International Commission on Snow and Ice (1975–1979)



Radok was born in Königsberg, East Prussia. As a young university student, he fled Germany for England with his two brothers as Nazism gripped Germany. In 1940, with the outbreak of war, he was interned in England and eventually (after surviving a vessel torpedoed en route to Canada) shipped to internment in Australia. After the war he completed a PhD under the noted meteorologist and polar explorer Fritz Loewe who, in Melbourne in 1937, had established the first Australian university meteorology department. He became Loewe's assistant after completion of his PhD and head of the department on Loewe's retirement.

His research interests covered a wide range of experimental and theoretical studies including atmospheric dynamics, numerical weather prediction, polar glaciology and climate science. In the early 1970s, he was a lead proponent of the *International Antarctic Glaciology Project* (IAGP), serving for many years as its executive secretary. He left Australia in 1977 for 2 years as the US National Science Foundation Office of Polar Programs, Glaciology Program Manager, and then for a decade at the Cooperative Institute for Research in Environmental Sciences, University of Colorado.

Box 6.

Box 7 Elizabeth (Liz) Morris (1946–)

President, International Commission on Snow and Ice (1995–2001)

Liz Morris grew up in London and studied physics at Bristol. Following her PhD (1972) she worked first on snow modelling and then on the mass balance and dynamics of polar ice sheets at the British Antarctic Survey (BAS), where she was Head of the Ice and Climate Division (1986–1999). Liz was the first woman to be a division head at BAS, the president of the ICSI and the president of the International Glaciological Society (IGS) (2002–2005). She was one of those who helped initiate changes within BAS which enabled female scientists to over-winter at Antarctic stations.

Liz served ICSI for 20 years in a number of roles, including two terms as president. She led the preparatory process that ultimately transformed the ICSI into the International Association of Cryospheric Sciences. During this she strongly advocated that an IUGG Association of Cryospheric Sciences and IGS, an independent scientific society, would play complementary roles in the science of snow and ice. In 2015 Liz was appointed an Honorary Member of IACS (see photograph in Box 8).

Box 7.

association commission be established before a new fully independent association.

Additional information, prepared by a Task Group of Gerry Jones, Georg Kaser and Roger Barry, was presented to the IUGG EC in Boulder in September 2004. The EC unanimously accepted that the ICSI become the Union Commission for the Cryospheric Sciences (UCCS) until ratification of a full new association by the IUGG Council at the next general assembly in 2007. The union commission was created to "prototype" IACS by creating a body separate from the IAHS that could demonstrate to the 2007 council that it had a constituency. It was a deliberate gestation period, and smoothed the way for a positive vote of the EC and the IUGG Council.

In 2005, Georg Kaser (Box 9) became president of the interim UCCS, charged with implementing the transition process and gaining its acceptance within the glaciological community. JoAnn Joselyn (secretary general of the IUGG) and Pierre Hubert (secretary general of the IAHS) were strong and crucial supporters within IUGG. During that time, UCCS officers recruited national committee members, drafted their statutes and by-laws, and all of the other associations (and especially IAHS) had time to adjust to the rather unsettling fact that they were going to have to share IUGG resources with another association.

On 4 July 2007, at the IUGG General Assembly in Perugia, the IUGG Council voted to establish an eighth association, the IACS. This was the first new IUGG associa-

Box 8 H. Gerald (Gerry) Jones (1936–)

President, International Commission on Snow and Ice (2001–2005)

Born in Wales, Gerry Jones emigrated to Canada in 1958 for post-graduate study. His research involves holistic studies of cryospheric ecosystems at different scales, with a particular focus on the relationships between the physical dynamics of snow and ice and nutrient pathways and associated metabolic processes in northern and sub-arctic Canadian forest and lake systems.

As the last ICSI president, Gerry worked tirelessly towards the establishment of an IUGG Cryospheric Association. With Georg Kaser and Roger Barry, he submitted the proposal that led to the formation of the UCCS to the IUGG Council at the 2003 General Assembly. He also drafted the statutes and by-laws for the new association, which IUGG later used as a basis for revision of its own statutes. In 2011 he was appointed as the first Honorary Member of IACS.

Three presidents during the transition period together at the 2015 IUGG General Assembly (Prague). From left to right: Liz Morris (Box 7), Georg Kaser (Box 9) and Gerry Jones (this Box).

Box 8.

tion in over 80 years. A new IAHS commission, the International Commission for Snow and Ice Hydrology (ICSIH), was also formed in 2007 to encourage research at the interface between cryospheric and hydrological sciences and to foster a fruitful connection with the IACS. Subsequently in July 2008, a Memorandum of Understanding was forged between IACS, the Scientific Committee on Antarctic Research (SCAR) and the International Arctic Science Committee (IASC) to recognize their common interest in ice and snow on Earth and to co-ordinate activities so as to avoid duplication and overlap.

6 The World Glacier Monitoring Service (WGMS)

This paper has recorded the transition from monitoring glacier variability in different parts of the world in response to climate fluctuations (the focus of CIG) to a broader consideration of the role of ice and snow in the total Earth system (IACS). But there is also an important and more direct legacy of the CIG coordination of international glacier monitoring. Although CIG activities were discontinued at the outbreak of war in 1914, glacier observations continued in different countries and the reporting was renewed with the formation of the IASH Commission des Glaciers in 1927 (Hamberg et al., 1930). They continued until 1959, throughout the difficult periods of the Great Depression and the Second World War, largely due to the efforts of Paul-Louis Mercanton (Switzerland). Mercanton led the compilation and publication of IASH reports on glacier length changes for 1913–1947 (Nos. 14, 20, 22, 30; for the Alps and Scandinavia, and later including Iceland) and for 1947–1959 (Nos. 32, 39, 46, 54; for Europe). In addition, IASH reports Nos. 20, 30, 32 and 39 contain glacier observations compiled for North America, one addendum for Sweden and two reports for Columbia and Peru respectively.

Box 9 Georg Kaser (1953–)
President, Union Commission for the Cryospheric Sciences (2005–2007)
President, International Association of Cryospheric Sciences (2007–2009)

Georg Kaser is a professor in the Institute for Atmospheric and Cryospheric Sciences at the University of Innsbruck, Austria. His research interests include the mass and energy balances of glaciers, fluctuations of climate and glaciers, and glaciology, climatology and hydrology in tropical mountain regions, especially the Cordillera Blanca, Peru, and Africa. Georg was a lead author of the cryospheric chapters of both the IPCC 4th and 5th Assessment Reports.

He played a lead role in the establishment of IACS as an independent association, spanning the transformation from ICSI (as secretary 1999–2003 and president-elect 2003–2005) through UCCS (president 2005–2007) to IACS (founding president 2007–2009). In 2015 he was appointed an Honorary Member of IACS (see photograph in Box 8).

Box 9.

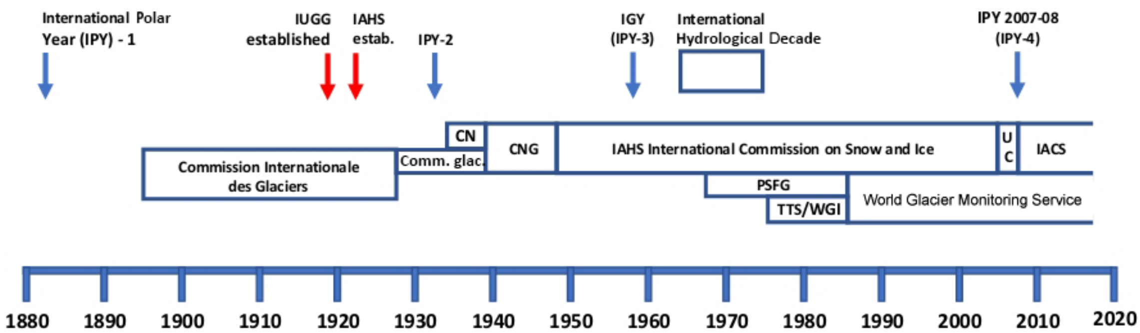


Figure 1. Schematic timeline showing the progression from the Commission Internationale des Glaciers (CIG) to the IUGG International Association of Cryospheric Sciences (IACS). This distinguishes two equally important heritage lines: monitoring glacier fluctuations and their link to climate (bottom) and cryospheric science more broadly (top). It also shows other major scientific programs and events relevant to the progression. (CN = IASH Commission des Neiges; Comm. Glac. = IASH Commission des Glaciers; CNG = IASH Commission des Neiges et des Glaciers; UC = IUGG Union Commission for the Cryospheric Sciences; PSFG = Permanent Service on the Fluctuations of Glaciers; TTS/WGI = Temporary Technical Secretariat for the World Glacier Inventory.)

On the initiative of Herfried Hoinkes, then president of the ICSI, a pilot study led by Peter Kasser was undertaken to set glacier variation surveys on a new and broader footing. This resulted in the 1967 formation of the Permanent Service on the Fluctuations of Glaciers (PSFG). In 1976, the Temporary Technical Secretariat for the World Glacier Inventory (TTS/WGI) was formed, and in 1986, on the initiative of Wilfried Haeberli, these two ICSI services combined to become the World Glacier Monitoring Service (WGMS).

Today the WGMS continues the collection and publication of standardized information on distribution and ongoing changes in glaciers that were commenced in 1894 (WGMS, 2017). It maintains a network of local investigators and national correspondents in all the countries involved in glacier monitoring. WGMS is co-responsible for the Global Terrestrial Network for Glaciers (GTN-G) within the Global Climate Observing System (GCOS) where it cooperates with the US National Snow and Ice Data Center (NSIDC) in Boulder and the Global Land Ice Measurements from Space (GLIMS) initiative. GTN-G aims to combine field observations with remotely sensed data, process understanding with global coverage, and traditional measurements with new technologies.

The WGMS is a service of IACS within the World Data System (WDS) of the International Science Council. WGMS provides a specific and expert technical function (compilation of standardized data on glacier changes in length, area, volume, and mass) whereas IACS covers a much broader perspective of cryospheric science, although the organizations work closely together. The two complementary streams of development from CIG in 1894 are shown in Fig. 1.

7 The International Association of Cryospheric Sciences (IACS)

Since it was formed in 2007, IACS has established itself as an active professional organization within the cryospheric sciences. Its primary objectives are to promote the advancement of cryospheric sciences of the Earth and the solar system; to encourage research in the cryospheric community through collaboration and international co-ordination; to promote education and public awareness on the cryosphere; and to facilitate the standardization of measurement or collection of cryospheric data and of their analysis, archiving and publication.

IACS is managed by an 11-member elected bureau comprised of the president, the president-elect or immediate past president, three vice presidents and the heads of five divisions covering different aspects of cryospheric science. The divisions are snow and avalanches; glaciers and ice sheets; sea ice, lake and river ice; cryosphere, atmosphere and climate; and planetary and other ices of the solar system. Bureau members are elected for a 4-year term and the Bureau meets at least once per year, although today often by teleconference.

IACS supports standing groups which address scientific problems of the cryosphere that require medium- to long-term reflection. Currently there are three standing groups: "Glacier and Permafrost Hazards in Mountains" (GAPHAZ; jointly with the International Permafrost Association, IPA), "IAVCEI/IACS joint commission on Volcano-Ice Interactions", and the "Global Terrestrial Network for Glaciers GTN-G Steering Committee". It also supports working groups which target timely and well-constrained scientific problems within a limited term (usually 4 years). These are initiated by members of the international scientific community, adopted with majority approval of the bureau, and managed within the most relevant IACS division. Currently, three working groups deal with improving our understanding different aspects of glaciers including the influence of surface debris cover on glacier mass balance, estimating ice thickness from unmeasured glaciers (Farinotti et al., 2017), and completing a standardized global inventory (Arendt et al., 2015). Two previous IACS working groups produced glossaries for glacier mass balance and snow, published by the UNESCO International Hydrological Programme. Both glossaries have become international standards and are highly cited and widely used in the cryospheric community (Fierz et al., 2009; Cogley et al., 2011).

Like all IUGG associations, the IACS organizes and supports major bi-annual scientific meetings. At the quadrennial IUGG general assemblies it promotes union symposia; joint symposia on climate change topics with the IAMAS, IAPSO and IAHS; and other joint symposia with the IAG (on satellite-based systems that are used to observe the cryosphere) and IASPEI (on "cryo-seismology", an exciting new field that provides insight into the structure and dynamics of glaciers and ice sheets, as well as the properties of the Earth's upper crust). At meetings midway between IUGG general assemblies it typically combines with other IUGG associations on an interdisciplinary theme, or with other cryospheric scientific organizations outside IUGG.

8 Future directions

The IACS is the youngest association of the IUGG, but at the same time it has a very long history when the precursor organizations discussed above are also included. As a new IUGG association, it is rapidly adopting new ways of working. The IACS actively promotes diversity within its structure. For example, the 11-member bureau for 2015–2019 included more than 50 % female scientists, scientists from 10 different countries and one early-career scientist. IACS also conducts much of its business via electronic communication, including video links and on-line voting on bureau resolutions.

IACS actively supports early-career scientists through provision of travel grants to sponsored scientific meetings and to international training courses, especially supporting student attendance from less-developed countries. It has also established a bi-annual cash prize awarded to two early-career scientists for the best scientific paper on a cryospheric topic.

IACS has offered an individual (free) membership since 2017. In the first 20 months, that grew to nearly 400 individual members.

Cryospheric science is a rapidly growing and evolving field, especially as impacts of climate change, such as glacier contributions to sea-level rise or rapid decline of sea ice, become increasingly evident and recognized. New technologies and remote sensing techniques have, at the same time, revolutionized the discipline. The IACS, particularly with its ability to quickly establish new working groups, is versatile, well-equipped and ready to contribute to meeting scientific challenges and further advancing cryospheric science.

Data availability. The data used for this paper are either available in publications of the CIG and of IAHS (*Red Book* series) or accessible as downloadable reports and minutes of UCCS and IACS meetings (http://www.cryosphericsciences.org/documents.html, last access: 21 December 2018).

Competing interests. The authors declare that they have no conflict of interest.

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Open Access History of Geo- and Space Sciences

IAHS: a brief history of hydrology

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Abstract. After describing the hydrological cycle and defining hydrology in the introduction, the early historical development of hydrology is briefly presented in the second section. Then the incorporation of hydrology within the IUGG and the subsequent development of the association are described chronologically. This description is organized into five sections corresponding to five different periods, focused on the scientific and organizational development of the association during each period. Finally, in the conclusions, the present state of the association is discussed together with an outlook for the future.

1 Introduction: what is hydrology?

Determining what happens to the rain when it hits the ground eventually leads to the concept of *the hydrological cycle*, which is the natural sequence through which water passes from vapour in the atmosphere to precipitation that on land separates into evaporation, transpiration and runoff to the sea, equalling net sea evaporation. *Hydrology* is the science that deals with the processes governing the depletion and replenishment of the water resources of the land areas of the Earth, and treats the various phases of the hydrological cycle. In a slightly extended wording, hydrology can be described as the science that deals with the waters above and below the land surface of the Earth, their occurrence, circulation and distribution, in both time and space, their biological, chemical and physical properties, and their reaction with the environment, including their relation to human beings.

When considering the central role of the hydrological cycle in the definition, hydrology is primarily thought of as a branch of *geophysics*, in the same way as oceanography and meteorology. In other contexts, where the emphasis is on water utilization, hydrology encompasses the broader concept of *water resources*, including societal relations, engineering and land use. This raises the argument over whether hydrology is a pure or applied science.

The many diverse forms and occurrences of water on the Earth, and the many different ways of utilizing water resources, gave rise to the concept of *the hydrological sciences*. These sciences (or branches of hydrology) include surface water, groundwater, water-related erosion and sediment transport, snow and ice, water quality, eco-hydrology, land–atmosphere interactions, catchment hydrology, flood forecasting, and water resources management. The list is endless and might also include the water on the Moon, Mars and other bodies in the solar system.

The development of hydrology in the 19th century was dominated by the emerging needs for *river engineering*, *water supply* and *urban drainage*. In the 20th century, hydrology gradually moved away from hydraulics and established its own scientific community. This went hand in hand with developments in data collection, which are indispensable for insight into the hydrological processes.

Towards the end of the last century, the growing *awareness of the environment* influenced hydrology such that environmental questions became a main driver for the development of the science. Pollution abatement, water resources assessment and nature conservation were, and still are, central issues. Today, other keywords are climate change impact, integrated approaches in catchment management, sustainable river basin management and uncertainty reduction in hydrological forecasting and prediction.

Figure 1. Leonardo da Vinci conducting experiments on the velocity-distribution in streams. Source: *Water Current Meters* by Frazier (1974).

2 Origin of hydrology as a science

Philosophical descriptions of the hydrological cycle were developed in ancient Asian and Middle Eastern civilizations, where large irrigation and flood protection works were carried out. The concept of hydrology was described in both the old Greek (e.g. Aristotle) and Roman (e.g. Marcus Vitruvius) cultures, where impressive water engineering projects were developed, such as aqueducts and bridges.

It was, however, not before the beginning of the 1500s that a scientific approach to hydrology started to take off, albeit with a very slow starting speed. Leonardo da Vinci undertook physical experiments, e.g. measuring stream velocity, to support his advanced thoughts about hydrology (Pfister et al., 2009). In 1575, Bernard Palissy, based on observations in nature, claimed that springs originated from rain, and 100 years later, in 1674, Pierre Perrault measured the rainfall, runoff and drainage area of the Seine River and concluded that rainfall was enough to support springs and rivers. The pathways, however, were not correctly described. In 1686, Edme Mariotte supported the findings of Perrault by contributing infiltration experiments, relating them to precipitation regimes and developing better streamflow measurements. Around 1700, Edmond Halley published the results of evaporation measurements, thereby contributing significantly to closing the hydrological cycle. Nevertheless, it was not before 1802 that John Dalton became the first to give a complete and correct description of the cycle based on reliable observations (Dooge, 1974; Rodda, 2006). Thus, it took 300 years to lay the foundations for modern hydrology.

In 1738, Daniel Bernoulli published the equation for frictionless pipe flow. The 18th century brought further progress. Laminar pipe flow and turbulent river flow were described by, respectively, Gotthilf Hagen and Jean Poiseuille in 1840 and Antoine Chézy in 1776. During the 19th century, engineering became an important driver for further progress in hydrology. The fundamental equation for groundwater flow was developed by Henry Darcy in 1856. Flow from urban catchments was addressed by introducing the time of concentration by Thomas Mulvany in 1850, leading to the rational method for peak flow design, and in 1883, Wenzel Rippl introduced the mass curve for reservoir design.

The first half of the 20th century brought additional basic development. A description of soil infiltration and saturation was provided by William Green and Gustav Ampt in 1911, while Weston Fuller introduced statistical frequency analysis in hydrology in 1914. Later fundamentals comprised the equation for unsaturated flow by Lorenzo Richards in 1931 and introduction of the unit hydrograph by Leroy Sherman in 1932. In 1935 Charles Theis presented the equation for the drawdown of the piezometric surface caused by pumping from a well, and finally, to conclude the 50 years, in 1948 Howard Penman developed an equation for estimating potential evaporation based on measured meteorological variables.

In the following, the main emphasis will be on the institutional development during the last centennial to support hydrology. For a more science-oriented description of the development, the reader is referred to Sivapalan and Blöschl (2017).

3 The start of the association and the first period, 1922–1939

At the general assembly of the IUGG in Rome in 1922, a delegate proposed a motion to form an additional section within the union to deal with the scientific problems in hydrology, such as "river-gauging, lake phenomena including seiches, run-off and evaporation, transport of material in suspension and in solution, glacier movement, etc." A committee was set up to give its opinion on the desirability of such a new activity. The committee gave favourable advice and proposed that the new organism should be named *Section of Scientific Hydrology*. The adjective "scientific" was added to distinguish the section's participants from the "charlatans and simpletons", who with the help of all sorts of rods tried to find water, calling themselves hydrologists, and also to make clear that the branch would not deal with the commercial exploitation of mineral waters. The first president was Edward Wade, who served from 1922 to 1933. (All subsequent presidents can be found at https://iahs.info/About-IAHS/Officers/Past-Presidents/, last access: 10 December 2018).

One of the reasons presented in the proposal was that the new organization would allow incorporation of the International Glacier Commission (CIG) that was founded in 1894, but had almost ceased to exist because of the First World War. At the 1924 General Assembly of the IUGG in Madrid, the Hydrology Branch created a "Commission for Glaciers" with the mission to assemble and publish data relating to glaciers. The inclusion of CIG in the Commission for Glaciers was approved at the Prague Assembly in 1927. Since snow is-

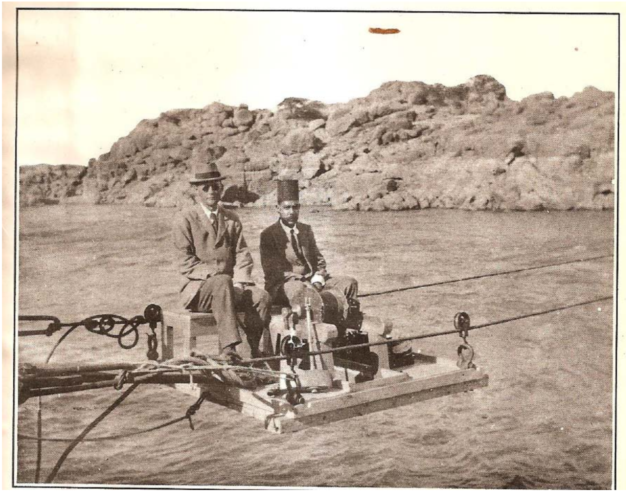

Figure 2. First IAHS President Edward Wade (left) taking flow measurements in the Nile River at Aswān in the early 1920s.

sues became of greater interest, a "Commission on Snow" was subsequently created in the early 1930s. At the Edinburgh Assembly in 1936, it was decided to amalgamate the two glaciological commissions into a new "Commission on Glaciers and Snow".

During the Madrid Assembly, a "Commission on Statistics" was constituted with the task of trying to bring some uniformity into the publication of hydrological data, and into the signs and symbols used. In addition, an effort was made to bring together data on the state of hydrology in different countries and to make an inventory of the water resources of these countries. The first publications of the branch comprised mostly national reports from this commission that served as background for two fundamental reports on, respectively, surface waters and subterranean waters. The scientists interested in this type of work were mostly hydraulic engineers, including teachers of hydraulics, who supplemented their teaching with the principles of hydrology. The report from the Madrid Assembly (IAHS, 1924) became the first in the *Series of Proceedings and Reports*, later known as *Red Books*. A complete list of the books is available at https://iahs.info (last access: 10 December 2018), where they can be either ordered (newer issues) or downloaded (older titles). During the 1933 Assembly in Lisbon, the branch was renamed the *International Association of Scientific Hydrology* (IASH).

Already in 1902, the first experimental basin study was initiated in the Emmental region of Switzerland (Whitehead and Robinson, 1993). In the 1930s, several additional studies were established assuming that in small experimental basins, it is easier to establish a water balance, and hydrological processes can be monitored and studied in detail. This methodology is generally accepted by the hydrological community as key to examining and observing small-scale hydrological phenomena.

The association began to cover an increasing number of hydrological disciplines, and new commissions on potamology, limnology, instruments and measurements, and subterranean waters were established. At the time of the Washington Assembly in 1939, the association had produced 27 publications in the series of Red Books. Because of the world war no IASH reports were published over the period 1939–1947. In 1935 the *International Association of Hydraulic Research* (IAHR) was created, which during the coming years led to a better distinction between hydrology and hydraulics.

4 Recognition and expansion of IASH, 1948–1970

Before World War II (1939–1945), hydrology, as it is understood today, was unknown to the public. Hydrology was not taught at universities as a separate subject. Fundamental aspects of it were included in such disciplines as physical geography and hydraulic engineering. However, during the period 1948–1970, hydrology became a generally recognized science of great significance for economic development. This had, of course, an enormous impact on the activities of IASH and its position in international scientific circles.

Post-war economic growth entailed a greater utilization of the natural resources of the Earth, water being one of the most important. Control and management of this resource became necessary in order to ensure adequate water supply for all sectors, together with flood forecasting and prediction. This could only be achieved by hydraulic works and structures, such as storage dams and reservoirs, diversion canals, embankments and groundwater recovery. The hydraulic design of these works required hydrological data extending over a sufficient number of years and sound knowledge of hydrological processes. This is especially true for the prediction of extreme events, such as major floods and serious droughts and their frequency of occurrence. Soon it was found that, in many cases, this sort of information was missing, and not only in developing countries. It was realized that the scarcity of hydrological information formed an obstacle to economic development, and that the water resources were limited even in humid zones. Thus hydrology, often mistakenly confused with water control, became an important discipline in the view of both decision makers and the public. This development lies behind the expansion of IASH in the period 1948–1970.

The meetings held during the General Assemblies of the IUGG in Oslo in 1948, in Brussels in 1951, and in Rome in 1954, were attended by an increasing number of participants of various backgrounds, such as hydraulic engineering, physical geography, geology, hydrometeorology and water management. A need was felt to organize more frequent meetings than would be possible within the framework of the union assemblies. The first meeting of this type was the

Darcy Symposium in Dijon in 1956 on the occasion of the centenary of Darcy's law, where not only groundwater but also evaporation and floods were discussed. The frequency of these meetings, organized independently from the Union, increased, and in the 1960s, hardly a year passed by without one or even two symposia being convened under the primary responsibility of the association. All proceedings were published in the *Red Books* series. In 1948, León Tison from Belgium had assumed the duties of secretary general, and for more than 20 years, he served the association with great devotion and zeal. Tison succeeded in having the papers printed near his home at low cost and with small delays, so that the publications could be available at the meetings. He did all the secretarial work and the management of the affairs of the association, assisted by his wife, son and daughter.

The *Red Books* became widely read amongst the hydrological community and sold well. The series was supplemented by a series on snow and ice, co-edited with UNESCO, starting in 1967 and mainly containing information on the fluctuation of glaciers. Most of the papers of the *Red Books* series in the period since 1948 dealt with fields that would soon be called "applied hydrology" or "engineering hydrology". They were grouped according to a new division of the association into commissions on surface water, groundwater, land erosion, and snow and ice. The books also contributed to the drafting of hydrological textbooks and handbooks. Before the 1940s, the only book on hydrology in English was Beardmore's *Manual of Hydrology*, dating back to 1862 (Beardmore, 1862). In 1942, a monograph was published by Meinzer as one of the volumes of a series on *Physics of the Earth* (Meinzer, 1942), and in 1949 the first modern book on hydrology, *Applied Hydrology* by Linsley, Kohler and Paulhus (Linsley et al., 1949), was published to complement hydraulic engineering. Since then many other books have been published.

Publication of the quarterly *Bulletin of the International Association of Scientific Hydrology*, written in French and English, was started by Tison in 1956. It contained reports of association meetings, news and reports of assemblies, as well as some scientific articles. It is the oldest of the scientific journals dealing with hydrology. Around 1960, the United Nations and its specialized agencies initiated comprehensive intergovernmental cooperation within the field of water.

While the International Meteorological Organization, founded back in 1873, had undertaken some hydrological activities, it was not until it was transformed into a full intergovernmental organization as *World Meteorological Organization* (WMO) in 1950 that it looked seriously at including hydrology as one of its responsibilities. In 1955, WMO set up a committee to advise on the matter, which included Tison as secretary general of IASH. When, 6 years later, WMO's commission on the subject met for the first time, it elected Tison as its first vice president, thereby cementing the firm link between the association and WMO that has existed ever since. Of direct relevance to hydrology was the establishment in 1961 of a "Commission for Hydrometeorology", soon to be renamed the "Commission for Hydrology".

In 1965, a major programme was launched by UNESCO as the *International Hydrological Decade* (IHD), one of the three "fathers" being Tison. There was widespread acceptance of the IHD, as a large number of member states committed themselves to jointly carry out a well-defined programme of hydrological studies and research extending over the 10 years. This was a novelty in UNESCO and considered as an experiment. One of the conditions for the success of the venture was a good understanding and cooperation with IASH, being a non-governmental organization. There was some doubt within the association as to whether an entity like UNESCO, dealing with both exact and human sciences, would be the most appropriate place for discussion of practical problems of hydrology and water resources development. However, Tison realized that the IHD would enable important projects to be started that were beyond the potential of IASH. Cooperation would be facilitated by the fact that many representatives of member states in the coordinating council were active participants in IASH. Consequently, the cooperation became very effective. IASH helped formulate programmes and contributed to the activities of working groups, many of which were reported on in the early volumes of the bulletin. Proceedings of symposia were organized and published jointly. The association also produced monographs on various subjects with UNESCO, but particularly on the subjects of snow and ice. A similar relationship was established with WMO within its programme on operational hydrology, but on a less formal basis.

The same economic factors that promoted the expansion of IASH during the 1960s also led to a spectacular increase in the activities of other technical organizations in the field of water: hydraulic research, irrigation and drainage, large dams, water supply, water pollution, and so on. All of these associations were established after 1950. They included in their programmes many topics that were closely related to the activities of IASH without creating serious competition or duplication at that time. A body for mutual consultation and coordination of the scientific and technical organizations was established later.

In 1964, the International Council of Scientific Unions (ICSU), which included the IUGG, created a *Committee on Water Research* (COWAR) to promote contacts between the Scientific Unions dealing with water issues. This concerned, in the first place, the IUGG and the unions on geological sciences, biological sciences and the geographical sciences, all belonging to the ICSU family. In 1994, the committee was substituted by the "Scientific Committee on Water Research" (SCOWAR) focussing on applied global hydrology, improved access to hydrological data worldwide and global freshwater assessments based on scientific understanding.

In 1967, it was decided that IUGG general assemblies should be convened every 4 years. This decision was of little consequence for IASH as most of its activities took place outside the union assemblies. More serious was the increase in workload of the IASH Secretary General (13 symposia and 25 publications in the period 1965–1969). Sadly Léon Tison suffered a stroke in November 1970, when he was about to leave home to travel to New Zealand to participate in a symposium on Representative and Experimental Basins. His ill health threatened the very existence of the association.

5 Transformation of IASH into IAHS and further growth, 1971–1981

When Tison was forced to relinquish his position, it became obvious that because of the increasing workload and concurrent thrusts in hydrology, as well as the new ideas about the grouping of the water sciences, the association needed a change. Consequently, a revised set of Statutes and Bye-laws was brought into force at the Moscow General Assembly in 1971, including a change in the name to the *International Association of Hydrological Sciences* (IAHS). This change reflected the broadening of hydrology. Likewise, the number of Commissions was increased in response to the growth.

A new management structure was devised to cope with the increasing number of activities and the growing work load. A treasurer and an editor were appointed to operate alongside the secretary general. Annual meetings of the bureau of the association were instituted at this time, and more frequent meetings were held between the president and secretary general. An editorial office – later named the *IAHS Press* – was established at the Institute of Hydrology, Wallingford, UK, in 1971, and another milestone was reached when *Red Book* No. 100 appeared later that year as the proceedings of the symposium Mathematical Models in Hydrology Part 1 (IAHS, 1971). In 1972, the IASH Bulletin became the *Hydrological Sciences Bulletin*, now containing many more scientific papers alongside reports of IAHS symposia, etc. To provide news of the association, the secretary general started to publish a newsletter, which was initially circulated to IAHS national committees and to members of commissions and committees.

Another major development in the period 1971–1981 was the reorganization of the scientific structure of IAHS. This had to be enhanced because of the considerable progress that had been made in the analysis of hydrological processes. Before that, many basic questions could only be answered by applying semi-empirical approaches. Better understanding and a more sophisticated and a higher conceptual level were reached by the application of system analyses, stochastic methods and analysis of time series. These techniques of applied mathematics had been developed at least two decades earlier, but it took a long time before they became part of hydrological practice. The term "parametric hydrology" came into being. A "Committee on Mathematical Models" was set up, which later received the status of "Commission on Water Resources Relations and Systems". The title indicates that the field of work had been broadened. Likewise, the scope of the "Geochemical Commission" was changed during the Moscow Assembly in 1971, reflected in the new name "Commission on Water Quality".

Figure 3. Brant Broughton gauging station, UK. Source: https://commons.wikimedia.org/wiki/File:Brant_Broughton_Gauging_Station_-_geograph.org.uk_-_1057107.jpg (last access: 10 December 2018); photo: Richard Croft (CC BY-SA 2.0).

When the IHD ended in 1974, the IAHS was one of the bodies that helped in the establishment of the permanent *International Hydrological Programme* (IHP) in UNESCO, a programme that was launched in 1975. The association took part in the conference to mark the end of the decade (UNESCO/WMO, 1974), a conference that became the first of the 6-yearly Joint Conferences on Hydrology convened by UNESCO and WMO. During this period, the association continued the policy of pre-publishing *Red Books* prior to the symposium concerned, the cost of one copy of the proceedings being contained within each registration fee.

Generally, the development of hydrology after 1970 became heavily influenced by the emergence of computers. Hydrological modelling, first in the form of lumped, conceptual models, changed the scene. Later, the more computer-demanding so-called physically based hydrological models appeared. Since that time the hydrological science, like most other sciences, has developed with ever-increasing speed.

6 IAHS in a changing environment, 1982–1999

During the 1980s, environmental change and particularly climate change became more prominent on the research agenda. The development of improved global circulation models seemed a dominant trend, but for hydrologists their inability to simulate the hydrological cycle with any degree of verisimilitude, and the difficulties of incorporating land–atmosphere relations in them, were considerable impediments to progress. This was frustrating, because the increased power of computers and the advent of PCs provided opportunities in hydrology to simulate hydrological systems to a much higher degree of accuracy than before. These opportunities were stimulated by the development of new sensors on the ground and on satellites, to the extent that remote sensing became an important tool for hydrologists.

In response to these developments, IAHS started its own series of scientific assemblies, the first being held in Exeter in 1982. The assembly attracted over 500 participants, and the proceedings were published in six volumes, with nearly 1800 pages. For the Hamburg IUGG General Assembly in 1983, in contrast to the 1970s, the associations in the IUGG were able to arrange their own programmes within the assembly, and the IAHS attendance and programme benefited considerably as a result. Later during this period, the number of committees in IAHS was increased, and the joint IAHS/WMO GEWEX (Global Energy and Water Exchange) Committee was established. Both of these actions resulted from the widening of the role of the association in response to the scientific challenges arising. The purpose of the GEWEX Committee was in particular to establish a visibility and role for hydrologists in the burgeoning field of large-scale hydrometeorological field experiments.

In 1981, the association, in cooperation with UNESCO and WMO, started the annual award of a silver medal, known as the *International Hydrology Prize*, to hydrologists who had made an outstanding contribution to the science. The prize was first awarded to Léon Tison for the excellence of his contribution to the association and for his expertise in research and skills in teaching. The prize has been awarded every year since to hydrologists who have distinguished themselves and brought credit to the science. Further, the Hamburg Assembly in 1983 agreed to establish an annual award to mark the contributions of young scientists to the association. The award, which is in the form of a certificate and the sum of USD 1000, as well as a year's free subscription to the journal of the association, is known as the *Tison Award*. It is bestowed for the best paper or papers published by IAHS in the preceding 2 years. The Hamburg Assembly also set up the *Hydrology 2000 Working Group*, a group of young hydrologists, who reported to the Vancouver Assembly in 1987 on the probable state and shape of hydrology in the year 2000.

In 1983, the name of the bulletin was changed to the *Hydrological Sciences Journal* (HSJ), and from 1988 it was published bimonthly. The proceedings of the 1984 symposium on Hydrochemical Balances of Freshwater Systems (Eriksson, 1984) appeared as IAHS Publication No. 150. Only 13 years had elapsed since Publication No. 100 was published, compared to 37 years between Nos. 1 and 50. The *IAHS Newsletter* was put on a more formal basis towards the end of the 1980s, being produced 3 times a year, with a circulation of up to 1000 copies to members as well as to UNESCO and WMO. Two new series of publications were launched in 1989: *IAHS Information in Chinese*, containing selected papers from HSJ and IAHS *Red Books*, was published 4 times a year as a bridge between IAHS and Chinese hydrologists, and a series of *Special Publications*, also known as *Blue Books*, written at the invitation of the association. The first *Blue Book*, with the title *Hydrological Phenomena in Geosphere–Biosphere Interactions* (Falkenmark, 1989) is out of print; other titles include *Leonardo Da Vinci's Water Theory: On the Origin and Fate of Water* (Pfister et al., 2009), and the last one *Changes in Flood Risk in Europe* (Kundzewicz, 2012).

Specialized symposia continued to be organized by the commissions and committees of the association, independent of general assemblies and scientific assemblies, to the extent that in the early 1990s, seven or eight *Red Books* appeared in most years. Indeed, in 1991 IAHS Publication No. 200 appeared as the proceedings of the Fourth International Symposium on Land Subsidence (Johnson, 1991). UNESCO provided financial support for this publication as a contribution to the IHP, while a number of other *Red Books* received financial support from WMO and a range of bodies and sources during the 1990s. Since 1992, there have been a series of colloquia, known as the *George Kovacs Colloquia*, which have been organized jointly by IAHS and UNESCO for two or three days directly before the meetings of the Intergovernmental Council of the IHP. The association continues to work closely with both UNESCO and WMO. IAHS is represented at the Council and Commission meetings and in the subsidiary bodies of both. UNESCO and WMO are represented at the meetings of the IAHS Bureau and play influential parts in the affairs of the association.

Intense debates took place within the association around 1990. It was contended that water resources management, and in particular flood frequency modelling, should not be considered part of hydrology. This contention was opposed by other hydrologists, who pointed to the many achievements emerging from engineering approaches in hydrology. To limit hydrology to a pure geophysical science would be unreasonable and harm the association. No one really won the argument, and the disagreements were eventually reconciled. What was left by the crusade was a strengthening of the links between hydrology and geophysics.

Probably the most important IAHS initiative in support of the transfer of knowledge to developing countries was started in 1991, when the association's "Task Force for Developing Countries" (TFDC) commenced the mailing of *Red Books* and, in some cases also the HSJ, to libraries in nations in need (as defined by the United Nations). Over 70 addresses in financially disadvantaged countries were selected, covering many countries in all continents, on the understanding that the publications were made available to hydrologists and other scientists outside the recipient organization. The list of addresses has been revised a number of times subsequently, but the main thrust of this important initiative is continuing in the free online access to HSJ for about 70 addresses, as well as for IAHS members in the TFDC countries.

7 The transformation of IAHS, 2000–2018

Two other heated debates within the association took place around the new millennium. One subject that involved much emotion was the wish of the glaciological community to leave IAHS in favour of a new cryosphere association within the IUGG. Snow and ice are integral parts of the hydrological cycle, and for that reason there was strong opposition in IAHS to accepting the new association. Again a compromise was achieved, which encompassed both a new glaciological association, the International Association of Cryospheric Science (IACS), in parallel to IAHS and a restructured commission on snow and ice hydrology within IAHS. Another subject was the suggestion that the commission structure should be abandoned and substituted by a purely project-driven organization. This was strongly contradicted by many hydrologists, who, among other things, pointed to the benefit of the many symposia organized by the commissions and working groups. No one could deny that a project structure might attract young hydrologists and revitalize the association, but it should not be at the expense of the advantages provided by the commissions. In the end, a compromise was achieved leading to a cross-cutting decadal project on prediction in ungauged basins, named PUB.

At present, there are few continuous flow records for most of the world's rivers. Where these measurements are made, they are subject to measurement errors, particularly during floods and droughts, the records can be short and interrupted, the calibration of the gauging stations can be poor and old records are often lost. River gauging is subject to cutbacks in government funding and is vulnerable to strife. However, reliable knowledge of flow and other hydrological variables is vital for planning and operating water resources projects, for flood forecasting and prediction, combatting water pollution and a host of other purposes. Such knowledge is the very basis of sustainable development.

The continued lack of comprehensive understanding about what happens to the rain at the catchment scale when it hits the ground surface has led to a plethora of models being developed and used for predicting runoff. These models differ markedly in their model concepts and structure, their parameters, and the inputs they use. They also differ in terms of which dominant processes they represent and the scales at which they make predictions. Most models are developed by different individuals and groups, with different disciplinary backgrounds; they benefit from local observations, experiences and practices that are influenced by local climate conditions and catchment characteristics. Consequently, they tend to have unique features not applicable in other places: every hydrological research group around the world seemingly studies a different object, their local catchment. The net result has been considerable fragmentation, "a cacophony" and a dissipation of effort that is not conducive to further advances.

In this context, the IAHS Decade on Predictions in Ungauged Basins was launched in 2003, aimed at achieving major advances in the capacity to make predictions in ungauged basins, through harnessing improved understanding of climatic and landscape controls on hydrological processes. The vision of PUB was to help a transformation "from cacophony to a harmonious melody". One of the clear tasks that the PUB initiative set out to achieve was to address the fragmentation of modelling approaches through comparative evaluation: "classify model performances in terms of time and space scales, climate, data requirements and type of application, and explore reasons for the model performances in terms of hydrological insights and climate-soil-vegetation-topography controls."

The decade was a great success in giving new momentum to IAHS. It attracted many young researchers around the world and created a forum for cooperation of the commissions. It succeeded in developing models to better predict availability of water in diverse climatic and economic circumstances and water-use settings, and to better forecast and predict floods and droughts in basins and regions in which there has been little or inadequate data on which to base models. The PUB decade resulted in three major publications: a review summary article in HSJ, "A decade of Predictions in Ungauged Basins (PUB) – A review" (Hrachowitz et al., 2013), and two books, *Runoff Prediction in Ungauged Basins – Synthesis across Processes, Places and Scales* (Blöschl et al., 2013), and *Putting Prediction in Ungauged Basins into Practice* (Pomeroy et al., 2013). These publications combine advancing the predictive capability and fundamental understanding of hydrological processes with making the findings relevant to the needs of societies in basins of all scales. The PUB initiative has brought together scientists, practitioners and policy makers from around the world and from many organizations, including UNESCO, in a cooperative effort.

Given the role of the IAHS as a leader in international hydrology, a new series of *Benchmark Papers in Hydrology* was launched in 2006 as a major effort for diffusion of the most important ideas in hydrology to libraries, institutes and individuals, interpreting the hydrological sciences in the broadest sense. The IAHS commission presidents served as editorial board members to the series. Each volume contains an Introduction prepared by the specialist volume editor together with commentaries; articles from the key papers of the 20th century are fully reproduced (exceptionally in part). In total, nine such volumes were published, starting with *Streamflow Generation Processes* (Beven, 2011), a selection of 31 papers spanning the period 1933–1984, commencing with Horton's early papers on infiltration and on maximum groundwater levels. The last book in the series *Paleohydrology* (Baker, 2014), provided a strong focus on palaeofluvial processes, especially palaeoflooding.

The success of the PUB decade made a follow-up essential. Consequently, IAHS launched, for the period 2013–

2022, a new scientific decade entitled Panta Rhei – Everything Flows (Montanari et al., 2013). The initiative is dedicated to research activities on change in hydrology and society. The purpose of the Panta Rhei initiative is to reach an improved interpretation of the processes governing the water cycle by focusing on their shifting dynamics in connection with rapidly changing human systems. The practical aim is to improve our capability to make predictions of water resources dynamics to support sustainable societal development in a changing environment. The concept implies a focus on hydrological systems as a changing interface between environment and society, whose dynamics are essential for determining water security, human safety and development, and for setting priorities for environmental management. The Panta Rhei scientific decade will devise innovative theoretical blueprints for the representation of processes including change and will focus on advanced monitoring and data analysis techniques. An interdisciplinary path will be sought by bridging with socio-economic sciences and geosciences in general.

The Panta Rhei decade has three clear objectives:

1. *Understanding.* This has always been the essence of hydrology as a science. Improving our knowledge of hydrological systems and their responses to changing environmental (including anthropogenic) conditions, and in particular variability and indeterminacy, is a key step in deciphering change and the interaction with society. Special attention is being devoted to complex systems, such as mountain areas, urban areas, alluvial fans, deltas and intensive agricultural areas, and to the specification of new measurement and data analysis techniques, which will allow the development of new understanding of co-evolution processes.

2. *Estimation and prediction.* This is closely related to understanding and is the essence of hydrologic engineering and hydrological applications, embracing flood risk mitigation and water resources management. This objective includes estimation of design variables under change and uncertainty assessment, which are crucial to support risk evaluation.

3. *Science in practice.* This signifies the aim to include humans in the study of hydrological systems and, therefore, to achieve an iterative exchange between science, technology and society. Science in practice is science for people. It is, therefore, relevant to science (both fundamental and applied) and relevant to water technology. It includes policy-making and implementation. The relevance of hydrology to society implies the identification of societal needs for water – for its various uses – as well as the threats that water poses in terms of flooding, land degradation and droughts. Here, we need a shift in paradigms of modern water management based on equities between demand- and supply-driven activities.

Figure 4. Flow measurements using a drone. Flight campaign by Sune Yde Nielsen, Henrik Karmisholt Grosen (Drone Systems.DK), Christian Josef Köppl and Filippo Bandini (DTU Environment).

The continuous fall in the number of river flow gauging stations and the decline of precipitation networks are challenging in hydrology. To circumvent this, new observational methods based on advanced technology are entering the scene. There is growing use of remotely sensed data from satellites, aircraft surveillance, weather radar and now from unmanned aerial vehicles (UAVs, i.e. drones). This trend will continue and is expected to provide new opportunities to hydrologists.

From 2014, IAHS, UNESCO and WMO decided to award two international prizes each year in place of the International Hydrology Prize; these were denoted the *Dooge Medal* and the *Volker Medal*, named after two of the early recipients of the International Hydrology Prize.

With the success of the updated IAHS website and online news, the free *IAHS Newsletter* was discontinued in 2014, and in 2015, the last *Red Book* was printed. In addition to their scientific value, the *Red Books* recorded the progress of the association and its science in a way unmatched by other IUGG associations and by the IUGG itself. For many years, the *Red Books* sales had provided an income for the association, but with the new era of electronic publishing, this was no longer the case. As electronic publishing is the preferred medium for proceedings, it was decided to stop printing books, while continuing to publish the series electronically as the *Proceedings of the International Association of Hydrological Sciences (PIAHS)*, with unbroken numbering and with free online access (and print on demand only). IAHS Publication No. 368 on *Remote Sensing and GIS for Hydrology and Water Resources* (Chen et al., 2015) was the last *Red Book* published in-house by IAHS.

8 Conclusions: the current state of IAHS

The IAHS Bureau governs the association; it consists of the president, the president-elect or immediate past president, three vice presidents, the secretary general, the treasurer, the editor-in-chief and presidents of the scientific commissions in existence at the time, as well as the chair of the International Association of Hydrological Sciences Limited. The final authority of the association in all matters of administration and finance is vested in the plenary administrative session of the association. It consists of the above persons plus one voting delegate from each adhering country. The company IAHS Ltd. deals, i.a., with the IAHS publishing programme, including the arrangements for the scientific journal. IAHS offers free membership and has currently 7000 members distributed throughout almost 200 countries.

With the activities of 10 commissions, 4 working groups and an ongoing, vibrant scientific decade, Panta Rhei, IAHS is in excellent shape. The commissions and working groups are as follows:

- International Commission on Surface Water (ICSW)
- International Commission on Groundwater (ICGW)
- International Commission on Continental Erosion (ICCE)
- International Commission on Snow and Ice Hydrology (ICSIH)
- International Commission on Water Quality (ICWQ)
- International Commission on Water Resources Systems (ICWRS)
- International Commission on the Coupled Land-Atmosphere System (ICCLAS)
- International Commission on Tracers (ICT)
- International Commission on Remote Sensing (ICRS)
- International Commission on Statistical Hydrology (ICSH)
- IAHS Working Group on Panta Rhei (everything flows)
- IAHS Working Group on Education in Hydrology
- IAHS Working Group on MOXXI (Measurements & Observations in the 21st Century)
- IAHS Working Group on CandHy (Citizen and Hydrology).

The work of the IAHS Task Force for Developing Countries continues. Hydrology in Wallingford takes care of the peer-review process of HSJ (which now has 3 co-editors and 48 associate editors) and its publication in partnership with the publishing company Taylor & Francis; the administration of the proceedings series (PIAHS), published by Copernicus; and provides support to the Bureau, maintaining the IAHS website (https://iahs.info/, last access: 10 December 2018) through the IAHS Executive Secretary.

The International Association of Hydrological Sciences is a coherent and well-integrated organization across all its different activities. Perhaps this is the reason why the wisdom of changing from "science" to "sciences" in 1971 has recently been challenged. Hydrology is today a well-defined science in its own right and not a collection of different sciences. A discussion is ongoing, and perhaps we will soon see a renaming of the association to, for example, *International Hydrology Association* (IHA). This, however, is a future decision.

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IAMAS: a century of international cooperation in atmospheric sciences

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Abstract. The International Association of Meteorology and Atmospheric Sciences (IAMAS) was founded in 1919 as the Section of Meteorology of the International Union of Geodesy and Geophysics (IUGG). Significant advances over human history, particularly during the 19th century, in the gathering, communication, assembly and analysis of observations of the changing weather and in theoretical understanding of the fundamental physical relationships and processes governing atmospheric circulation had been driven by the need for improved weather and climate forecasts to support the expansion of global trade, better public warnings of extreme weather, and safer and more effective military operations. Since its foundation, in parallel and cooperation with intergovernmental development under the auspices of what is now the World Meteorological Organization (WMO), IAMAS and its 10 international commissions have provided the international organizational framework for the convening of the general and scientific assemblies and other meetings that bring together expert scientists from around the world to further advance scientific understanding and prediction of the behaviour of the atmosphere and its connections to and effects on other components of the Earth's intercoupled geophysical system.

1 Introduction

The successes and failures of societies around the world have been and continue to be dependent on weather and climate, especially because of their critical role in determining the availability of vital agricultural, ecological and hydrological resources. Many of the deities of the earliest civilizations represented weather- and climate-related phenomena, becoming a mechanism for organizing, explaining and passing along relationships and linkages that had been gained from prolonged observation of the timing and variability of seasons, monsoons and other phenomena to future generations. Significant departures from the expected patterns were often memorialized as conflicts between conflicting deities with such fidelity that many of the events have since been identified in paleoclimatic records.

In Greece in the fourth century BCE, Aristotle[1] and Theophrastus prepared treatises describing the collective wisdom of their time, hypothesizing that various interactions among the four bodies of fire, air, water and earth provided explanations for the observed weather and climate. About 50 BCE, Andronikos Cyrrhestes constructed a 12 m high, octagonal horologium (known now as the Tower of Wind), which is viewed as the first meteorological observatory, serving as a sundial, water clock, compass and weather vane, with stone carvings representing each of the eight directions from which Athens' winds came over the course of the year. For many centuries, expectations regarding atmospheric phenomena were based almost solely on relationships involving Sun angle and the changing positions of constellations. Speculations were mainly qualitative with little capability of linking together what was happening in different locations

[1]Aristotle's treatises described what was known about meteorology, a term of Greek origin meaning atmospheric disturbances.

through understanding of the intercoupled nature of the atmosphere, oceans and cryosphere.

As exploration and travel expanded, assembly and comparison of information from different regions led to observations of prevailing wind regimes and ocean currents and correlations of phenomena across regions and with geophysical events such as volcanic eruptions. Making progress, however, required both (1) instruments that could quantify observations for analysis and display as maps and (2) advances in understanding of atmospheric physics and chemistry that would eventually provide a more rigorous basis for analysis and forecasting. Advances in both areas were spurred by increasing demands for better understanding of the range of meteorological conditions that could affect public safety, military planning and actions, and expansion of trade and the global economy.

The second and third sections of this paper highlight a number of early advances with relevance to the atmospheric sciences and the gradual awareness about the need for increasing international cooperation to accelerate progress in understanding of atmospheric behaviour and for forecasting. These advances provided essential groundwork that enabled the foundation of the forerunner of today's International Association of Meteorology and Atmospheric Sciences (IAMAS) after the severe historical incision of World War I. The fourth and fifth sections describe the formative years of IAMAS following World War I and then key developments of the association since that time. Tabulated biographical information about the 35 individuals who have served as the president and/or secretary-general is also included to provide a sense of the broad spectrum of interests of those in the international scientific community that have contributed to the development of IAMAS. The sixth section provides a summary of the establishment, primary focus and key scientists that played roles in the formation and development of the 10 international commissions that form the backbone of IAMAS. The final section then contains a few concluding remarks.

2 The early development of instruments and assembly of observations

The quest for useful observations was significantly advanced in the 1600s when Italian polymath Galileo Galilei invented the thermometer, Italian physicist Evangelista Torricelli invented the barometer and Dutch physicist Christiaan Huygens invented the pendulum clock. During the 18th century, French nobleman Antoine-Laurent de Lavoisier, in addition to organizing understanding of chemistry by establishing the periodic table, was instrumental in identifying that the atmosphere contained, among other components, both oxygen and water vapour, the latter becoming an especially important variable to observe.

By the early 1800s, international trade led to sufficient observations being taken that initial climatological maps could start to be prepared, giving indications of typical conditions by latitude and longitude. It was not until the second half of the 19th century, however, that there were sufficient data and insights to allow preparation of synoptic maps showing such features as cyclonic and anti-cyclonic circulations and indications of their movement in time and changes in intensity. As information was accumulated, climatologies were developed to provide information for improving the routing and safety of the rapidly increasing number of sailing ships. The increasing utility of observations led directors of national meteorological services to agree in the late 19th century to standardize measurement techniques.

Assembly of information was further advanced in 1837 by American Samuel Morse's invention of the telegraph, which soon led to communication lines for rapidly transmitting and receiving observations around the world. The first reliable cable across the Atlantic Ocean began service in 1866, with further installations helping to reduce the time for assembling observations from days and weeks to hours and, starting with the first transatlantic radio communication in 1901, to minutes.

An important limitation to advancing understanding, however, was that virtually all of the regular observations were of conditions at the surface, the few exceptions including cloud type, height and cover (changes of which became an important basis for early weather forecasting); atmospheric scattering (leading to the empirical forecasting adage: "Red sky at night, sailors' delight. Red sky at morning, sailors take warning"; cf. Library of Congress, https://www.loc.gov/rr/scitech/mysteries/weather-sailor.html, last accessed 25 January 2019); sunspot number (as a proxy for changes in solar radiation); and, beginning at a very limited number of locations in the late 19th century, observations of winds aloft using pilot balloons.

Driven by their desire to better understand the weather and climate in the adjacent North Atlantic, Norwegian meteorologist Vilhelm Bjerknes and oceanographer Bjørn Helland-Hansen each established institutes at the University of Bergen in 1917 that were particularly important in advancing understanding of atmospheric fronts, air–sea interactions, and other features that proved essential for forecasting system behaviour over ensuing days. During World War I, aircraft observations aloft started to become available, setting the stage for significant improvement in weather forecasts.

3 The early development of scientific understanding

In parallel with the development of observations leading up to the 20th century, advances were made in understanding the physics and chemistry of the atmosphere. The perfect law of gases (also known as Boyle's law after Anglo-Irishman Robert Boyle) and recognition of the three laws of motion put forth by England's Sir Isaac Newton in the late 17th and early 18th centuries provided the foundation for developing an understanding of global atmospheric circulation patterns. In 1735 George Hadley, an amateur English meteorologist, published a paper expanding upon English astronomer Edmond Halley's earlier explanation for the trade winds. Hadley's explanation was based primarily on consideration of the buoyancy of hot air and the Earth's rotation. The resulting circulation he derived featured a single cell extending from the Equator to high latitudes. American William Ferrel reworked the analysis in the 19th century, conserving angular rather than linear momentum, and proposed the three-cell structure recognized today, which has the Ferrel cell located between the low-latitude Hadley cell and the high-latitude Arctic circulation.

In 1824, French scientist Joseph Fourier first published an explanation for the near stability of the Earth's temperature, indicating that downward emission of infrared radiation from the atmosphere played a critical role (Fourier, 1824, 1827). The fundamental laws for thermodynamics were also formulated during the period, with many of the insights coming as a result of seeking to understand the behaviour of gases, particularly those in the atmosphere. In particular, experiments by English physicist (and brewer) James Joule and theoretical work by German physicist Rudolf Clausius established the relationship between work and heat and, with later involvement of William Thomson (later Lord Kelvin), led to the development of the law of conservation of energy as the first law of thermodynamics. Clausius was also responsible for contributing to development of the second law of thermodynamics, which posited that entropy always increases (sometimes stated as heat flows from hot to cold) and deduced what became the Clausius–Clapeyron relationship that, in the meteorological field, determines the saturation water vapour mixing ratio at various temperatures. Adding insights from experimental studies he began in the 1850s, Irish physicist John Tyndall presented proof that water vapour and carbon dioxide (CO_2) were the most important atmospheric gases contributing to what is now called the "greenhouse effect"[2], providing a strong intellectual framework for understanding the global energy balance and the thermodynamic effects of many atmospheric processes (Tyndall, 1861).

During the same period, Scottish geologist Charles Lyell, building on the reasoning of fellow countryman James Hutton, argued that the Earth's features were a result of slow processes acting over long periods of time (uniformitarianism), rather than being mainly responses to short-term, catastrophic changes, thus rejecting notions derived from biblical genealogies that the Earth's age was only several thousand years. In books first published in the early 1830s, Lyell (1830, 1832, 1833) went on to define and distinguish geological strata (and the climatic conditions that must have been prevailing), clarifying the differences among earlier geological eras (i.e. Palaeozoic, Mesozoic and Cenozoic) and periods (e.g. dividing the Tertiary into the Pliocene, Miocene and Eocene).

Lyell's contributions over the next few decades also contributed critical information underpinning the scientific studies of England's Charles Darwin, setting atmospheric (and geophysical) scientists on a quest to document and explain changes in climate in terms of their causes. The proposal by Swedish scientist Svante Arrhenius in 1896 that changes in the atmosphere's CO_2 concentration could help explain Earth's climatic history led directly to his prediction that the future climate would become warmer as a result of ongoing fossil-fuel emissions (Arrhenius, 1896). Through laborious calculations, he became the first scientist to calculate the sensitivity (i.e. responsiveness) of the climate to a doubling of the CO_2 concentration, arriving at a value only slightly higher than today's central estimate. That it took over half a century for his hypothesis to be accepted was the result of two key criticisms: (1) the large carbon-holding capacity of the oceans would limit the potential rise in the atmospheric CO_2 concentration (a criticism not convincingly refuted until the ocean tracer studies by American oceanographer Roger Revelle and Austro-American chemist Hans Suess in the 1950s; Revelle and Seuss, 1957) and (2) CO_2 absorption in the atmosphere was already saturated (a criticism not convincingly refuted until the one-dimensional radiative-convective model simulations of Japanese-American meteorologist Syukuro Manabe and American meteorologist Richard Wetherald in the 1960s showed the importance of the change in altitude at which saturation occurred; Manabe and Wetherald, 1967).

With quantitative understanding developing, British mathematician (and later meteorologist) Lewis Fry Richardson made the first attempt to actually calculate the evolution of the weather over one 6 h time step by quantitatively representing each of the many processes thought to alter atmospheric temperature, water vapour, pressure and winds (Richardson, 1922). Gathering all the available data for 20 May 1910 for a region in central Europe, he spent idle time while serving as an ambulance driver during World War I undertaking the extensive calculations by hand. While the forecast was unsuccessful for various reasons, the stage was set for developing numerical forecasting capabilities over ensuing decades.

4 The start of IAMAS: formation in 1919 and topics at the 1922 assembly

Organized international cooperation in meteorology goes back to the mid-19th century, with the first international conference convening in Brussels in 1853 (Ismail-Zadeh, 2016). Naval representatives from 10 nations (eight western Euro-

[2] The term "greenhouse" has become widely used even though the actual physics keeping greenhouses warm is a result of limiting the escape of water vapour from the glass-enclosed structure.

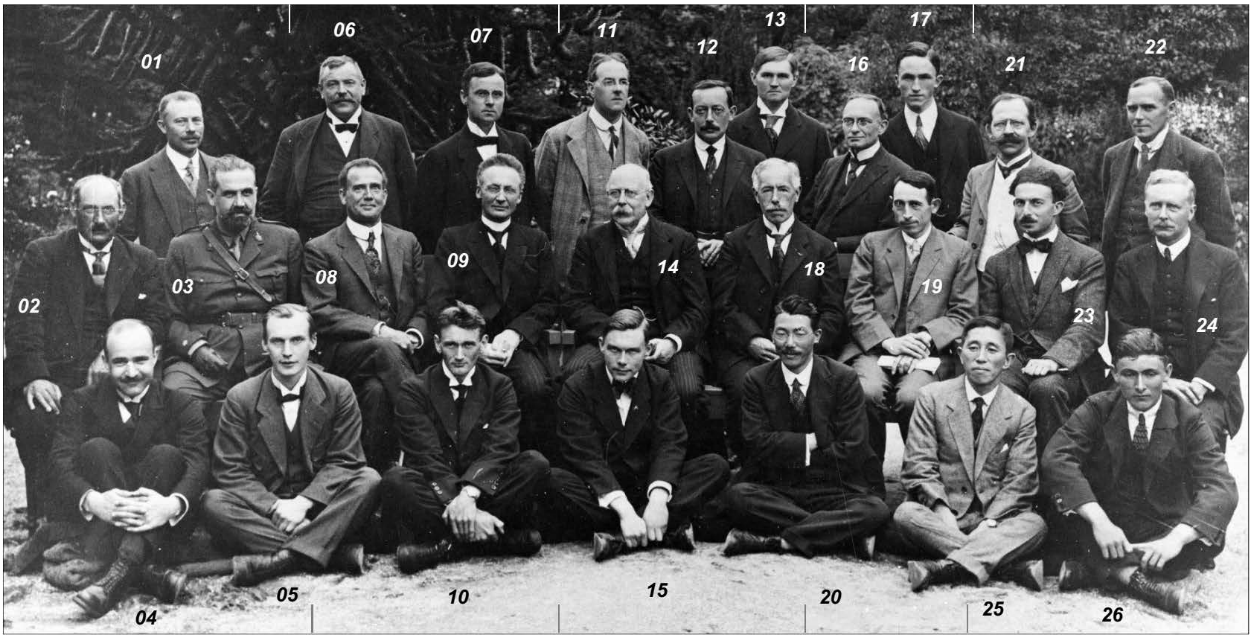
01 Maurits SNELLEN *(51)* *(Netherlands; 1840–1907)*
02 Fritz ERK *(34)* *(Germany, Bavaria; 1857–1919)*
03 Léon TEISSERENC de BORT *(36)* *(France; 1855–1913)*
04 Clement WRAGGE *(39)* *(Australia; 1852–1922)*
05 Robert H. SCOTT *(58)* *(Great Britain; 1833–1916)*
06 Mark W. HARRINGTON *(43)* *(USA; 1848–1926)*
07 Karl KLENGEL *(25)* *(Germany, Bavaria; 1866–1930)*
08 Karl MACK *(34)* *(Germany, Württ.; 1857–1934)*
09 Ernst BIESE *(35)* *(Finland; 1856–1926)*
10 Stefan HEPITES *(40)* *(Romania; 1851–1922)*
11 Hugo HILDEBRANDSSON *(53)* *(Sweden; 1838–1925)*
12 Carl LANG *(42)* *(Germany, loc.host; 1849–1893)*
13 Christoph SCHULTHEISS *(31)* *(Germany, Baden; 1860–1918)*
14 Henrik MOHN *(56)* *(Norway; 1835–1916)*
15 Adolphus GREELY *(47)* *(USA; 1844–1935)*
16 Julius HANN *(52)* *(Austria; 1839–1921)*
17 Henry H. CLAYTON *(30)* *(USA; 1861–1946)*
18 Eleuthère MASCART *(54)* *(France; 1837–1908)*
19 Władysław KWIETNIEWSKI *(54)* *(Poland; 1837–1902)*
20 Hugo HERGESELL *(32)* *(Germany, Alsace; 1859–1938)*
21 Arthur von OETTINGEN *(55)* *(Estonia; 1836–1920)*
22 Adam PAULSEN *(58)* *(Denmark; 1833–1907)*
23 Adolpho P. PINHEIRA *(40)* *(Brazil; 1851–19yy)*
24 Heinrich WILD *(58)* *(Russia; 1833–1902)*
25 W. BOEDL *(xx)* *(Germany, Bavaria; 18xx–19yy)*
26 Cleveland ABBE *(53)* *(USA; 1838–1916)*
27 Max ESCHENHAGEN *(33)* *(Germany, Prussia; 1858–1901)*
28 Spas VATSOV *(35)* *(Bulgaria; 1856–1928)*
29 Georg NEUMAYER *(65)* *(Germany, Hamburg; 1826–1909)*
30 Robert BILLWILLER *(42)* *(Switzerland; 1849–1905)*
31 Abbott L. ROTCH *(30)* *(USA; 1861–1912)*
32 Augusto ARCIMIS *(47)* *(Spain; 1844–1910)*
33 Paul SCHREIBER *(43)* *(Germany, Saxony; 1848–1924)*
34 Wilhelm von BEZOLD *(54)* *(Germany, Prussia; 1837–1907)*

Surnames following www.digiporta.net/index.php?id=653862969

Figure 1. Participants at the International Conference of Directors of Meteorological Services, in Munich, Bavaria, Germany, 26 August–2 September 1891, 28 years prior to the formation of the Section of Meteorology. Numbering is in six columns, from left to right, with the following information for each person: number, first name, surname (age at conference, representative for country or state, and lifespan). The surnames follow the handwritten note attached to the copy kept at Deutsches Museum, Digitales Porträtarchiv, Munich, Germany (cf. website http://www.digiporta.net; last access: 25 January 2019). The high-resolution scan was provided by the National Meteorological Library and Archive in Exeter, UK.

pean nations plus the USA and Russia) focused their attention on the need to improve and expand observations for weather forecasting. Their efforts eventually led to the first International Meteorological Conference in Vienna in 1873 and the formation of the International Meteorological Organization (IMO) in 1879 (and, much later, inspired the formation of the World Meteorological Organization (WMO) in 1950). The IMO was led by an International Meteorological Committee composed of the directors of the meteorological services of the member nations.

An early example of such international cooperation is documented in the group photograph taken during the summer of 1891 at the International Conference of Directors of Meteorological Services held in Munich, Germany (Fig. 1). Among the 34 attendees from more than a dozen nations on three continents were Georg Neumayer (pioneer of Southern Hemisphere meteorology) and Wilhelm von Bezold (thermodynamicist who defined potential temperature) from Germany, Cleveland Abbe (early proponent of dynamical meteorology) from the USA, Julius Hann (global-scale collector of vast climatological datasets) from Austria, and Léon Teiserrenc de Bort (specialist in vertical soundings and co-discoverer of the stratosphere a decade later) from France. Although most participants represented fledging meteorological services, they met as experts in a personal, non-governmental capacity and set out to distribute tasks among technical commissions (Davies, 1990, p. 4), as is still done by both IAMAS and WMO. The International Commission on Radiation and Insolation formed in 1896 (Bolle, 2008) and the International Commission for the Scientific Investigation of the Upper Air were two of the very early commissions.



01 Martin Knudsen *(50)* *(Denmark; 1871–1949)*
02 Axel Wallén *(44)* *(Sweden; 1877–1935)*
03 Juan Cruz-Conde *(45)* *(Spain; 1876–1941)*
04 Ernst Calwagen *(27)* *(Sweden; 1894–1925)*
05 Oscar Edlund *(29)* *(Sweden; 1892–1959)*
06 Johan Sandstrøm *(47)* *(Sweden; 1874–1947)*
07 Theodor Hesselberg *(36)* *(Norway; 1885–1966)*
08 Willem van Bemmelen *(53)* *(Netherlands; 1868–1941)*
09 Vilhelm Bjerknes *(60)* *(Norway; 1861–1952)*
10 Hilding Köhler *(33)* *(Sweden; 1888–1982)*
11 Lewis Fry Richardson *(40)* *(Great Britain; 1881–1953)*
12 Paul Louis Mercanton *(45)* *(Switzerland; 1876–1963)*
13 Harald Norinder *(33)* *(Sweden; 1888–1969)*
14 Napier Shaw *(67)* *(Great Britain; 1854–1945)*
15 Finn Malmgren *(26)* *(Sweden; 1895–1928)*
16 Jules Jaumotte *(34)* *(Belgium; 1887–1940)*
17 Jacob Bjerknes *(24)* *(Norway; 1897–1975)*
18 Ewoud van Everdingen *(48)* *(Netherlands; 1873–1955)*
19 Ernest Gold *(40)* *(Great Britain; 1881–1976)*
20 Sakuhei Fujiwara *(37)* *(Japan; 1884–1950)*
21 Alfred de Quervain *(42)* *(Switzerland; 1879–1927)*
22 Geoffrey I. Taylor *(35)* *(Great Britain; 1886–1975)*
23 Philippe Schereschewsky *(29)* *(France; 1892–1980)*
24 Charles J.P. Cave *(50)* *(Great Britain; 1871–1950)*
25 Rikichi Sekiguchi *(35)* *(Japan; 1886–1951)*
26 Gustav Gyllström *(18)* *(Sweden; 1903–19xx)*

Figure 2. Participants at the eighth meeting of the International Commission for the Scientific Investigation of the Upper Air on 25 July 1921, in Bergen, Norway, 2 years after the formation of the Section of Meteorology. Numbering is in five columns, from left to right, with the following information for each person: number, first name, surname (age at conference, country of work – not necessarily nationality – and lifespan). The high-resolution scan was provided by the University Library in Bergen, Norway.

As World War I was coming to a close in late 1918, leading scientists in the allied nations began advancing plans for peaceful cooperation and scientific advancement under the League of Nations. That international cooperation in the development and application of meteorological observations and forecasting had been going on for a half-century provided a strong basis for the effort to expand such cooperation across a broader spectrum of the geophysical sciences. Led by representatives of the national academies of science of the various nations[3], discussions and planning meetings led, within a year, to the formation of the international scientific structure that has persisted for virtually all of the period since (Shaw, 1923). The International Research Council (IRC) was formed first and held its first plenary meeting in Brussels in late July 1919 (Schuster, 1921; the IRC was the predecessor of the International Council of Scientific Unions – ICSU, recently merged with the International Social Science Council to form the International Science Council). The International Union for Geodesy and Geophysics (IUGG) was established within the IRC. It was composed initially of six sections, one being the Meteorology Section (Bauer, 1919a).

At the Brussels plenary, Sir Napier Shaw of UK's Royal Society was appointed President of the Bureau for the Section de Météorologie, hereafter referred to as the Meteorology Section. Shaw had emphasized greater reliance on science (as opposed to empirical analysis) in his leadership of the British Meteorological Office during World War I (including by employing Lewis Richardson). Charles Alfred Angot, earlier Directeur du Bureau Central Météorologique de France, was selected as vice president, and Charles F. Marvin, then chief of the US Weather Bureau, was selected as secretary (Bauer, 1919b). While each

[3]That leaders of meteorological sciences in the national academies were also often leaders in their government's activities was relatively unique across the geophysical sciences, showing in a very real sense how scientific advances in atmospheric sciences could rapidly be applied by governments for the benefit and safety of their citizens and economic and governmental activities.

had been or was a leader of their government's meteorological service, the Meteorology Section was a creation of the national academies of science of the participating countries rather than of government meteorological organizations. The focus of the non-governmental effort was intended to be on the scientific questions arising in the study of meteorology and geophysics in contrast to the more empirical and observational emphasis of the governmental efforts that were focused mainly on operational forecasting and ensuring public safety. That these efforts had been ongoing together for so long provided a strong basis for their ongoing cooperation and connection.

Each nation was called upon to have a national committee for IUGG, providing a member to serve as a representative to each of its sections; this requirement proved instrumental in spurring organization and cooperation among each of the disciplines in the member countries. Members of the atmospheric science community were active participants in the organizational efforts (Shaw, 1923). For example, climatologist Hubert Lamb was included along with those affiliated with the UK Meteorological Service as UK's representatives; France formed an IUGG national committee, of which 49 of its 124 members were affiliated with the Section of Meteorology; and in the USA, formation of the national committee spurred organization in 1919 of both the American Meteorological Society and what later became the American Geophysical Union (Wood, 1920).

The photograph of participants at the eighth meeting of the International Commission for the Scientific Investigation of the Upper Air (Fig. 2) held in Bergen, Norway, in 1921 shows many of those who were engaged with the early development of the Section of Meteorology, including Sir Napier Shaw (the section's founding president), Vilhelm Bjerknes (who served as president from 1935–1936) and his son Jacob Bjerknes (who served as secretary-general from 1936 to 1948 and president from 1951–1954). Right from the beginning, the enthusiasm for international cooperation on a voluntary basis appears to have been a natural and steady ingredient of most gatherings of IUGG's sections and their successors (cf. Gold, 1921; Volkert, 2017). A brief but vivid eyewitness account was provided some 55 years after the meeting in Bergen by Schereschewsky (1977), including succinct appraisals of later achievements by some of the participants.

By providing their sections with an annual allocation from the collective dues paid by the national academy of each of the 20 initial member nations, IUGG provided resources for their Sections to actually organize research activities. This was in contrast to the IMO, which did not at that time provide funds to promote cooperative activities. That this effort to promote international research was seen as a particularly important endeavour by the participating nations is suggested by the fact that the US Congress explicitly endorsed the effort and specifically allocated funding for IUGG membership in its annual budget actions over IUGG's first several years.

The first major action of the Meteorology Section's Bureau was to call for proposals from the national committees for research topics and questions to be placed on the agenda for the first IUGG general assembly to be held in Rome in 1922. In his report to the Royal Meteorological Society, Shaw (1923) explained 11 topical areas (or "gaps of knowledge") that had been submitted by the national committees of Great Britain, France and Italy (collected in Table 1). Many of the suggested topics continued to be of such interest that they later became the basis for formation of many of the commissions that now exist.

Nine nations are reported to have sent delegates to the first meeting of the Meteorology Section at the Rome general assembly: Australia, Belgium, France, Great Britain, Italy (in large numbers), Portugal, Spain, Sweden and the USA. Resolutions approved were related to the following subjects (Kimball, 1922), which were closely linked to the abovementioned topical areas:

1. allocating much of the Section's funding to initiate an enhanced network of balloon sondes to explore the upper atmosphere;

2. allocating much of the remaining resources for study of the stratosphere through expansion of the pilot–balloon network, especially in the desert regions and around the Equator;

3. developing a cooperative field and theoretical programme on convection;

4. preparing a report on the effects of radiation on atmospheric circulation, including by taking measurements at different mountain observatories around the world (this resolution led to establishment of the Commission of Solar Radiation in 1924 with Herbert H. Kimball from the US Weather Bureau as president);

5. purchasing and distributing a number of instruments to measure haze;

6. developing the capability to measure hydrogen at different locations and altitudes;

7. surveying the methods of doing weather forecasting around the world;

8. collaborating with the Commission on Clouds formed by the International Meteorological Committee (IMC);

9. promoting application of modern statistical methods to calculate normals;

10. meeting with the International Meteorological Committee to discuss potential overlaps and cooperation.

Table 1. Numbered topics (“gaps in our knowledge”) outside of the routine investigations of meteorological services, suggested by three National Committees of IAM for discussion at the general assembly of 1922 in Rome (Shaw, 1923).

Country	no.	Topic
Great Britain	01	Lack of observations of temperature and wind velocity in the upper air over the sea and over deserts or inhospitable regions
	02	Which observers worldwide pay attention to the actual detail of convection as prerequisite for rainfall?
	03	What are immediate and longer-term effects of active convection on the surrounding atmosphere?
	04	Role of radiation in the sequence of weather and for the large-scale vertical circulation
	05	Impairment of visibility, measurements of hygroscopic aerosols to address atmospheric pollution
	06	Composition of the atmosphere above 100 km. Is hydrogen main constituent at such heights?
France	07	Different sorts of thunderstorms and, more generally, electrical phenomena
	08	Transparency of the atmosphere and its optical phenomena
	09	Different sorts of clouds
	10	Forecasting weather, in particular the method of tendencies (isallobars)
Italy	11	Necessity for presenting normals of meteorological data according to modern statistical methods

5 Growing international cooperation in atmospheric sciences

Following the general assembly in Rome in 1922, the Meteorology Section met every 3 years (except for the years during World War II) as part of the triennial general assemblies of IUGG until the IUGG decision in 1967 to meet every 4 years (see Ismail-Zadeh and Joselyn, 2019). At the fifth IUGG general assembly in Lisbon in 1933, it was decided to refer to the IUGG Sections as Associations, and so the Meteorology Section was renamed the International Association of Meteorology (IAM); it was then renamed the International Association of Meteorology and Atmospheric Physics (IAMAP) at the 11th IUGG general assembly in Toronto in 1957. Nearly 4 decades later, recognizing the very important role of other traditional scientific disciplines in atmospheric studies, the name was officially changed to the International Association of Meteorology and Atmospheric Sciences (IAMAS) at the 21st general assembly held in Boulder in 1995. Hereafter in this chapter, the association’s current name will be used.

Since its beginning, IAMAS has been led by a president, with administrative and organizational activities directed by a secretary-general nominated by the national committees that are members of IUGG. New officers are elected at each of the IUGG general assemblies to serve from the conclusion of that gathering through the next general assembly. Succinct biographical information and portraits are provided for all 23 presidents in Table 2 and Fig. 3 and for all 12 secretaries-general in Table 3 and Fig. 4. All of the officers have been trained as scientists, but they come from a broad range of disciplines, including geography, meteorology, physics, astronomy and mathematics. Up to the 1970s, many of the officers were employees of the national meteorological services, while since then their primary employment has been by universities and research laboratories.

From the time of its formation, IAMAS has been cooperating with the international meteorological organizations organized by the world’s national governments. With the formation of the United Nations, IMO’s role was taken over by the World Meteorological Organization (WMO) in 1950 (Davies, 1990). A formal agreement between IUGG and WMO was worked out in 1953 that has governed their respective roles since that time, with WMO taking the leading role in organizing meetings of the international meteorological service organizations and IUGG (through IAMAS) organizing meetings aimed at advancing the science of meteorology. To ensure ongoing cooperation, IUGG has, since signing the agreement, appointed a formal liaison with WMO, often a scientist drawn from IAMAS.

A major undertaking of IUGG and its associations in cooperation with other international unions and entities was sponsorship and organization of the International Geophysical Year (IGY) in 1957–1958. Along with later satellite-based data, data from the expanded observation network established during IGY has made clear that Planet Earth must be considered as an integrated whole. To ensure ongoing cooperation in observations and research, ICSU created the Scientific Committee on Oceanic Research (SCOR) in 1957 and the Scientific Committee on Antarctic Research (SCAR) in 1958 to promote interdisciplinary science on the oceans and Antarctica, respectively. Ever since then, IAMAS has had representation in these organizations, participating in their governance on behalf of IUGG.

Beginning in the 1970s, IAMAS and the other IUGG Associations began holding their own (sometimes joint) Scientific Assemblies in the years between the quadrennial IUGG general assemblies (Table 4). The first such IAMAS Scientific Assembly was convened jointly with the International Association of the Physical Sciences of the Ocean (IAPSO) in Melbourne in 1974. The assembly drew participation from nations on both sides of the “Cold War,” an openness to all

Table 2. Succinct biographical information about the 23 persons who have served as IAMAS presidents; photographs are presented in Fig. 3. Under academic training, the subject of graduation is listed (typically for a PhD or MSc degree).

no.	First name, surname	Country (of work)	Office term	Lifespan	*Academic training*; primary expertise (role at meteorological service – mets)
01	W. Napier Shaw	UK	1919–1930	1854–1945	*Physics*; atmospheric dynamics and synoptics (director, UK mets)
02	Axel Wallén	Sweden	1930–1935	1877–1935	*Geography*; climatology, agricultural meteorology (director, Swedish mets)
02a	Vilhelm Bjerknes[a]	Norway	1935–1936	1862–1951	*Physics*; atmospheric dynamics and synoptics, forecasting
03	Sidney Chapman	UK	1936–1948	1888–1970	*Mathematics*; geomagnetism, kinetic theory of gases
04	Jacob Bjerknes	USA	1948–1951	1897–1975	*Physics*; forecasting, dynamics, oceanography
05	Kalpathi Ramanathan	India	1951–1954	1893–1984	*Physics*; geophysical observations, aerology (director, Indian mets)
06	Carl-Gustaf Rossby	Sweden	1954–1957	1898–1957	*Mathematics*; forecasting, dynamics, atmospheric chemistry
07	Jacques van Mieghem	Belgium	1957–1960	1905–1980	*Mathematics*; geomagnetism, aerology (director, Belgian mets)
08	Horace R. Byers	USA	1960–1963	1906–1998	*Geography*; synoptic and aviation meteorology (scientist, US mets)
09	Alexander M. Obukhov	USSR	1963–1967	1918–1989	*Physics*; theory of atmospheric turbulence
10	Reginald C. Sutcliffe	UK	1967–1971	1904–1991	*Mathematics*; forecasting, dynamics (research director, UK mets)
11	Sigmund Fritz	USA	1971–1975	1914–2015	*Mathematics*; solar radiation, satellite meteorology
12	Christian Junge	FR Germany	1975–1979	1912–1996	*Meteorology*; atmospheric chemistry, aerology
13	Warren L. Godson	Canada	1979–1983	1920–2001	*Chemistry*; forecasting, aerology (research director, Canadian mets)
14	Hans-Jürgen Bolle	Austria	1983–1987	1929–2013	*Physics*; radiation, satellite meteorology
15	G. Brian Tucker	Australia	1987–1991	1930–2010	*Mathematics*; global circulations, atmospheric chemistry (scientist, Austral. mets)
16	Brian J. Hoskins	UK	1991–1995	1945–	*Mathematics*; dynamics of weather and climate
17	Robert A. Duce	USA	1995–1999	1935–	*Chemistry*; atmospheric and marine chemistry
18	Huw C. Davies	Switzerland	1999–2003	1944–	*Mathematics*; atmospheric dynamics, modelling
19	Michael C. MacCracken	USA	2003–2007	1942–	*Applied science*; modelling, climate change, paleoclimate
20	Guoxiong Wu	China	2007–2011	1943–	*Meteorology*; forecasting, dynamics, mountain effects
21	Athéna Coustenis	France	2011–2015	1961–	*Astronomy*; planetary atmospheres, comparative climatology
22	John Turner	UK	2015–2019	1953–	*Meteorology*; forecasting, polar meteorology, climate change

[a] Vilhelm Bjerknes was vice president of IAM when president Axel Wallén died in 1935; Bjerknes then acted as president during the meteorology sessions at the IUGG general assembly held in 1936 in Edinburgh.

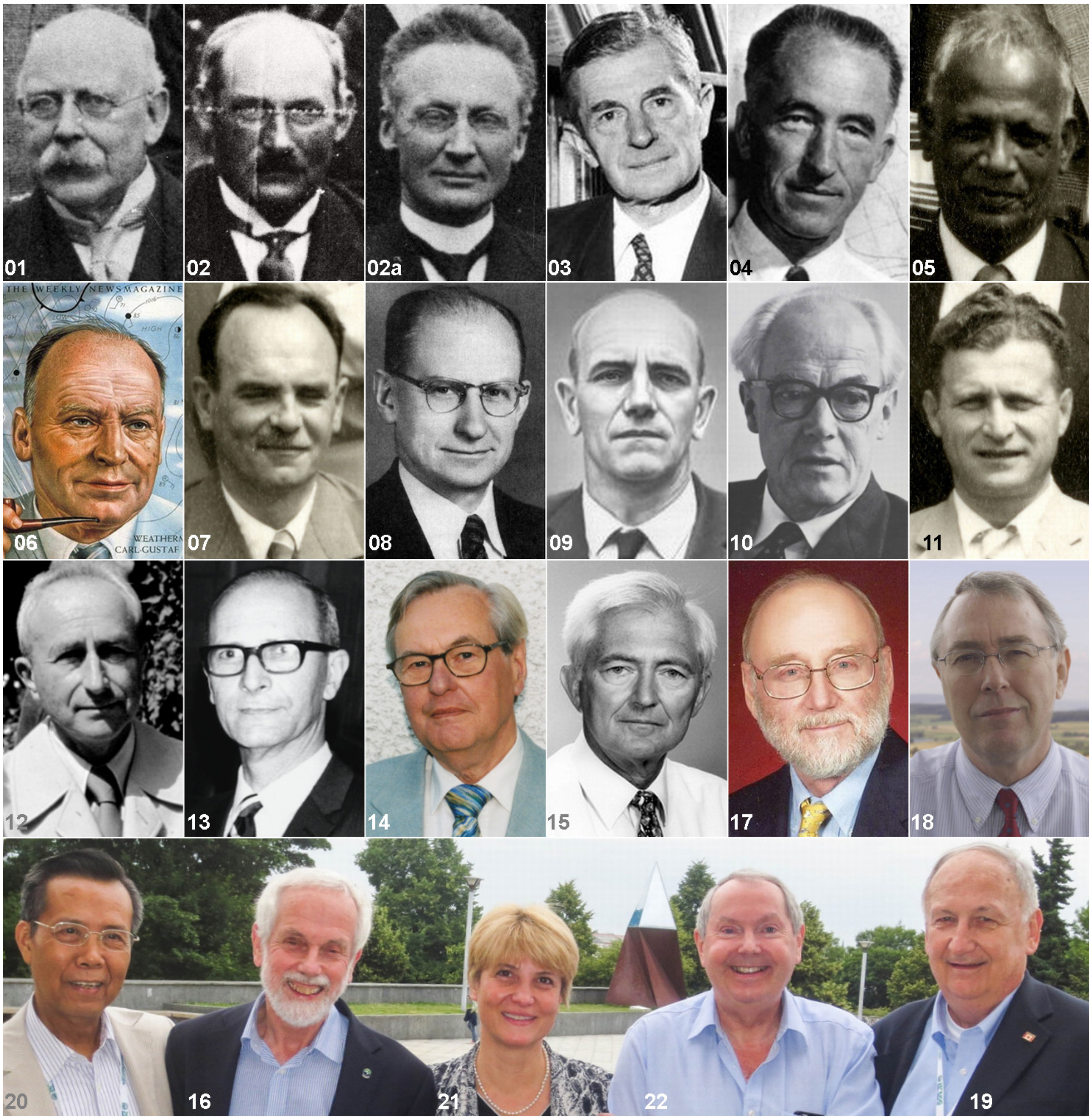


Figure 3. Collection of portraits of the 23 IAMAS presidents serving from 1919 to 2019: **(01)** Napier Shaw, **(02)** Axel Wallén, **(02a)** Vilhelm Bjerknes (acting president after Wallén's death in 1935), **(03)** Sidney Chapman, **(04)** Jacob Bjerknes, **(05)** Kalpathi Ramanathan, **(06)** Carl-Gustaf Rossby, **(07)** Jacques van Miehgem, **(08)** Horace Byers, **(09)** Alexander Obukhov, **(10)** Reginald Sutcliffe, **(11)** Sigmund Fritz, **(12)** Christian Junge, **(13)** Warren Godson, **(14)** Hans-Jürgen Bolle, **(15)** Brian Tucker, **(16)** Brian Hoskins, **(17)** Robert Duce, **(18)** Huw Davies, **(19)** Michael MacCracken, **(20)** Guoxiong Wu, **(21)** Athéna Coustenis and **(22)** John Turner. See Table 2 for detailed information. Photo credits: the bottom row depicts five presidents (no. **16**, **19–22**) together at IUGG-2015 in Prague (positions not in chronological order), © Maggie Turner; for **06**, © Time Magazine, vol. 68, no. 25, 17 December 1956; no. **01**, **02** and **02a**, cuttings from Fig. 2; no. **05**, **07** and **11**, cuttings from group photograph of 1959 (© B. J. Harris; Ohring et al., 2009); no. **3** and **13** from Bojkov, 2012; and other portraits from web sources.

that IUGG and its associations now enshrine. Given the geophysical continua of the solid, liquid, and gaseous Earth, atmospheric studies under the umbrella of IAMAS benefitted significantly from the advances in observations and understanding led by a number of its sister associations, primarily involving IAGA (Mandea and Petrosky, 2019), IAPSO (Smythe-Wright et al., 2019), IAHS (Rosbjerg and Rodda, 2019) and IACS (Allison et al., 2019).

The variable climatic conditions of the 1970s and the emerging indications that human activities were starting to influence the climate led to formation of the World Climate Research Programme (WCRP) by ICSU (IUGG's parent or-

Table 3. Succinct biographical information about the 12 persons who have served as IAMAS secretaries-general; photographs are presented in Fig. 4. Under academic training, the subject of graduation is listed (typically for a PhD or MSc degree).

no.	First name, surname	Country (of work)	Office term	Lifespan	*Academic training*; primary expertise (role at meteorological service – mets)
01	Charles F. Marvin	USA	1919–1922	1858–1943	*Meteorology*; design of instruments (chief, US mets)
02	Filippo Eredia	Italy	1922–1927	1877–1948	*Physics*; forecasting, especially for aviation (director, Italian mets)
03	Philippe Wehrlé	France	1927–1936	1890–1965	*Engineering*; synoptics, atmospheric turbulence (director, French mets)
04	Jacob Bjerknes	Norway–USA	1936–1948	1897–1975	*Physics*; forecasting, dynamics, oceanography (director, western Norway mets)
05	Jacques van Mieghem	Belgium	1948–1954	1905–1980	*Mathematics*; geomagnetism, aerology (director, Belgian mets)
06	Reginald C. Sutcliffe	UK	1954–1960	1904–1991	*Mathematics*; forecasting, dynamics (research director, UK mets)
07	Warren Godson	Canada	1960–1975	1920–2001	*Chemistry*; forecasting, aerology (research director, Canadian mets)
08	Stanley Ruttenberg	USA	1975–1987	1926–2017	*Physics*; international manager for NAS, IGY, GARP
09	Michael Kuhn	Austria	1987–1995	1943–	*Atmospheric physics*; radiation, aerosols, glaciology
10	Roland List	Canada	1995–2007	1929–2019	*Physics*; cloud physics, weather modification (deputy secretary-general, WMO)
11	Hans Volkert	Germany	2007–2015	1955–	*Meteorology*; mesoscale dynamics, field campaigns
12	Teruyuki Nakajima	Japan	2015–2019	1950–	*Atmospheric physics*; radiation, climate

ganization) and WMO in 1980, with UNESCO's Intergovernmental Oceanographic Commission joining as a sponsor in 1993. The WCRP Joint Scientific Committee (JSC) was formed, drawing members from both the governmental and non-governmental scientific community. The JSC and a sister body under the International Geosphere Biosphere Programme (IGBP) organized a number of major projects, often in cooperation with IUGG and its various components (including IAMAS and its commissions), covering the Earth system from the surface to the stratosphere and the tropics to the poles as well as physical, chemical and biological processes from the hydrologic cycle to cycling of atmospheric pollutants. Over ensuing decades, IAMAS has appointed representatives to participate in both planning meetings and project activities, especially when the area of study has included the atmosphere.

6 The backbone of IAMAS: its 10 international commissions

The wide range of topics considered at the Rome general assembly made clear that the scope of important topics encompassed in atmospheric sciences is large. With observation and research efforts intensifying through the 20th century, the number of specialists in each of the particular areas grew, leading to IAMAS adopting an internal structure that would promote focused development and cooperation in each area while still encouraging integration across the study of meteorology and atmospheric sciences.

To accomplish this, IAMAS has, over its history, established 10 scientific commissions (see Table 5). Each commission has a particular scientific focus and its own set of officers and members. In addition to describing the scientific scope of each commission, the following paragraphs list a few of the many scientists from around the world who have been responsible for advancing understanding in each area, generally focusing on those involved in the early to mid-20th century and even before. A good number of these commissions have become so large that they convene their own scientific meetings, typically bringing together hundreds of scientists, most often in years other than those when IUGG general assemblies and IAMAS scientific assemblies are held. In addition to meetings held under IUGG and IAMAS auspices, many of the commissions also arrange to meet jointly with other IUGG associations or are involved with them in related or co-sponsored international scientific programmes. In addition, commission members often serve as representatives to or are on the leadership teams for scientific projects

Figure 4. Collection of portraits of the 12 IAMAS secretaries-general serving from 1919 to 2019: **(01)** Charles Marvin, **(02)** Filippo Eredia, **(03)** Philippe Wehrlé, **(04)** Jacob Bjerknes, **(05)** Jacques van Mieghem, **(06)** Reginald Sutcliffe, **(07)** Warren Godson, **(08)** Stanley Ruttenberg, **(09)** Michael Kuhn, **(10)** Roland List, **(11)** Hans Volkert and **(12)** Teruyuki Nakajima. See Table 3 for detailed information. Photo credits: **03** and **04**, cuttings from group photograph of 1936 (Bojkov, 2012; Fig. 4; © Oxford University); **05–07** cuttings from group photograph of 1959 (© B. J. Harris; Ohring et al., 2009); **09** and **11** in October 2011 (© Markus Weber); **12** in June 2015 (© Hans Volkert); and other portraits from web sources.)

sponsored by other international bodies. A comparison of the leading scientists mentioned in the commission highlights below with the names of officers listed in Tables 2 and 3 reflects the organizing notion of IUGG that its associations have officers drawn from those who can be prominent and knowledgeable spokespersons for the scientific areas encompassed by its commissions.

6.1 International Radiation Commission

The approval of IAMAS Commissions began in 1948 when the International Radiation Commission (IRC) was formed by merging the existing Commission of Solar Radiation with the considerably older Radiation Commission that had been chartered by IMO in 1896. A comprehensive history has been compiled by German-Austrian scientist Hans-Jürgen Bolle (2008), while American George Ohring et al. (2009) described joint undertakings with the International Ozone Commission since a conference that was held in Oxford, UK, in 1959.

In its earliest days, the focus was on the development and accuracy of instruments and measurement techniques in order to generate better understanding of the transmission of solar radiation through both clear and cloudy conditions, particularly seeking to determine if and how the Sun's output has been changing. Complicating the determination of solar variability have been natural and human-caused atmospheric aerosols of various types. Among the leading radiation scientists during these formative years of IRC and earlier were Jules Violle and C. Alfred Angot (both France), Anders Ångström (Sweden), Jules Maurer and Walter Mörikofer (both Switzerland), Fritz Möller (Germany), Kirill Ya. Kondratyev (USSR), Giichi Yamamoto (Japan), Sir John Houghton (UK), and Herbert H. Kimball and Julius London (both USA).

Through the 20th century, there has been increasing attention devoted to the determination and calculation of infrared radiation and how the many gases in the atmosphere, especially gases being augmented by human-caused emissions, are influencing and strengthening the atmosphere's absorption and emission of infrared radiation, both upward toward space and downward toward the surface, thus strengthening the natural greenhouse effect. The understanding gained regarding the Earth's radiation and energy balance has proved essential in improving understanding of both natural variability and long-term climate change, including how past changes in solar insolation, volcanic aerosol loading, land cover change and human activities, particularly fossil-fuel combustion, have together affected the Earth's energy balance and the resulting weather and climate. With solar radiation essential for food production, ecosystem growth, and direct and indirect forms of renewable energy, among many other societal and ecosystem interactions, the scope of IRC's scientific coverage remains broad and critical.

Table 4. General information about special IAMAP (no. 01–05) and IAMAS (no. 06–13) scientific assemblies convened between the general assemblies of IUGG, from 1974 onwards. For earlier assemblies, see the table of locations of general assemblies provided in the article on the history of IUGG (Ismail-Zadeh and Joselyn, 2019).

no.	Year	Location	Country	Continent	Joint with	Acronym	Number delegates
01	1974	Melbourne	Australia	Australia	IAPSO		600
02	1977	Seattle	USA	North America	IAGA		950
03	1981	Hamburg	FR Germany	Europe			820
04	1985	Hawaii	USA	North America	IAPSO		450
05	1989	Reading	UK	Europe	IAPSO		1020
06	1993	Yokohama	Japan	Asia	IAHS		450
07	1997	Melbourne	Australia	Australia	IAPSO		1100
08	2001	Innsbruck	Austria	Europe			850
09	2005	Beijing	China	Asia			840
10	2009	Montreal	Canada	North America	IAPSO, IACS	MOCA-09	450
11	2013	Davos	Switzerland	Europe	IACS	DACA-13	950
12	2017	Cape Town	South Africa	Africa	IAGA, IAPSO		1000
13	2021	Busan	South Korea	Asia	IAPSO, IACS	MOCA-21 (being planned)	

Table 5. International commissions (IC) within the International Association of Meteorology and Atmospheric Sciences, listed by year of formation.

Year	Acronym	Name	Link to website (last access for all URLs: 25 January 2019)
1948	IRC	International Radiation Commission	http://www.irc-iamas.org
1948	IO_3C	International Ozone Commission	http://www.io3c.org
1953	ICCP	IC on Cloud and Precipitation	http://www.iccp-iamas.org
1966	CNAA	Committee on Nucleation and Atmospheric Aerosols	http://www.icnaa.org
1957	ICACGP	IC on Atmospheric Chemistry and Global Pollution	http://www.icacgp.org
1963	ICPM	IC on Polar Meteorology	http://www.icpm-iamas.aq
1967	ICDM	IC on Dynamical Meteorology	http://icdm.atm.ucdavis.edu/ICDM.html
1977	ICCL	IC on Climate	http://www.iccl-iamas.net
1977	ICPAE	IC on Planetary Atmospheres and their Evolution	http://icpae.iaps.inaf.it
1979	ICMA	IC on the Middle Atmosphere	http://icma.iaa.es
1989	ICAE	IC on Atmospheric Electricity	http://icae.jp

6.2 International Ozone Commission

Noticing the sharp cut-off in the radiation spectrum at UV wavelengths, Marie Alfred Cornu (France) was the first to suggest in 1879 that this was due to atmospheric absorption (Cornu, 1879). A year later, Sir Walter Noel Hartley (UK) suggested that absorption by ozone was the cause; the absorption band is now named after him (Hartley, 1880). Together they recognized that the ozone must be present in the upper atmosphere, being formed there by the missing UV radiation. While early observations showed variations through the year, it took until the invention of the spectrometer in 1924 by British physicist and meteorologist Gordon Dobson for there to be an instrument that could be used to make reliable and comparable measurements around the world.

The first international Conference on Ozone was held in Paris in 1929 and the second in Oxford in 1936 (Meetham, 1936). An expression of interest in becoming affiliated with the Section of Meteorology led initially to formation of a Committee on Ozone by the Commission on Solar Radiation; it was this committee that was recognized as the International Ozone Commission (IOC) in 1948 (Bojkov, 2012). Leading scientists in this early progression included Gordon Dobson (UK), Charles Fabry (France), Marcel Nicolet (Belgium), Sydney Chapman and Sir David R. Bates (both UK), Anna Mani (India), and F. W. Paul Götz (Switzerland), with Dobson becoming the IOC's first president.

The availability of a strong understanding of stratospheric ozone chemistry became critical in the 1970s as threats to its vital role emerged as a result of proposals for establishing a fleet of supersonic passenger aircraft and then as a result of the rising emissions of chlorofluorocarbons (CFCs) and other halocarbons. Observations and analyses of stratospheric ozone depletion and then the Southern Hemisphere's springtime "ozone hole" prompted international adoption of the Montreal Protocol and subsequent amendments. Since then, there has been the start of a recovery (not to mention that cutting CFC emissions has also been an important contribution to cutting greenhouse gas emissions). Scientific advances in this field were internationally recognized in 1995 with the award of the Nobel Prize in chemistry given to Paul Crutzen (the Netherlands and Germany), Mario Molina (Mexico and USA) and F. Sherwood Rowland (USA).

6.3 International Commission on Clouds and Precipitation

The International Commission on Clouds and Precipitation (ICCP) was the third IAMAS Commission to be established, being approved in 1953 and holding its first official meeting in 1954. Clouds and precipitation have been of interest from earliest times and have been regularly recorded by weather stations since the second half of the 19th century. To help improve consistency in observations, the IMO created a Clouds Commission that issued the first edition of the *Cloud Atlas* in 1896 (International Meteorological Committee, 1896); it has been regularly updated since. Clouds have been of particular importance because of their value in understanding atmospheric circulation, particularly relating to atmospheric moisture and precipitation and their role in affecting the energy and water balances. The ICCP created a Committee on Nucleation and Atmospheric Aerosols in 1966 to bring even more focused attention to the science of cloud microphysics, tropospheric and stratospheric aerosols, and aerosol–climate interactions.

Leading scientists in the early development of understanding of clouds, precipitation and convection included Tor Bergeron (Sweden), Horace Byers and Joanne Simpson (both USA), Tetoya “Ted” Fujita (Japan and USA), Sir John Mason (UK), and Hans Pruppacher (Germany). With fresh water being an absolutely vital resource for the world’s growing population, developing the capabilities for forecasting precipitation and changes in its distribution and intensity over time will be essential for sustaining the world’s peoples and communities.

6.4 International Commission on Atmospheric Chemistry and Global Pollution

The fourth commission created by IAMAS was the International Commission on Atmospheric Chemistry and Radioactivity, which was approved in 1957 and was most focused on urban pollution and fallout from nuclear testing. It was renamed the International Commission on Atmospheric Chemistry and Global Pollution (ICACGP, later iCACGP) in 1971, recognizing that the chemistry and composition of the atmosphere was really an issue that reached from urban to global scales and that, with the phasing out of nuclear testing in the mid-1960s, surface deposition of air pollutants, especially the sulphate compounds that caused acid precipitation, had replaced radioactivity as a more immediate issue of societal and ecological concern.

iCACGP’s members played a leading role in establishing the International Geosphere Biosphere Programme (IGBP), which coordinated studies in the area from 1987 to 2015, and initiating and sponsoring a number of important international research projects, including IGAC (International Global Atmospheric Chemistry), SOLAS (Surface Ocean–Lower Atmosphere Study) and iLEAPS (the Integrated Land Ecosystem–Atmosphere Processes Study). IGAC, SOLAS and iLEAPS are all now core projects within ISC’s Future Earth[4], which has succeeded IGBP. Some of the leading scientists in this research area in the mid-20th century and latter half of the 20th century included Christian Junge (Germany and USA); Bert Bolin, Henning Rodhe and Erik Eriksson (all Sweden); Paul Crutzen (the Netherlands and Germany); C. David Keeling, Lester Machta, F. Sherwood Rowland, Robert Duce and Robert Charlson (all USA); Mario Molina (Mexico and USA); Hans-Walter Georgii and Dieter Ehhalt (both Germany); Sean Twomey and Ian Galbally (both Australia); and Davendra Lal (India).

iCACGP’s efforts are now especially focused on how atmospheric composition and deposition of various pollutants interface with and affect such basic societal issues as water supply and quality, food production, and human and ecosystem health in a changing climate. With the world population growing rapidly, urbanization increasing, forest fires becoming more intense and dependence continuing on sources of energy that pollute the atmosphere, understanding how to ensure a healthy atmosphere has become a very wide ranging research area and a challenge of existential importance for science and society as the Anthropocene evolves.

A celebration of the 60th anniversary of the commission’s creation was held at the recent joint 14th iCACGP quadrennial symposium and 15th IGAC science conference (http://icacgp-igac2018.org, last access: 25 January 2019), which brought together ∼ 700 participants in Takamatsu, Japan. This gathering exemplified the scientific respect and organizational strength of the IAMAS commissions. The Japanese hosts underscored the importance of existing international organizations in promoting the development of a nation’s scientific community, as has happened, for example, for atmospheric chemistry in Japan over the past several decades.

6.5 International Commission on Polar Meteorology

In the late 19th and early 20th centuries, explorers were finally able to reach both poles. The International Polar Years of 1882–1883 and 1932–1933 led to significant advances in understanding, but it was not until the International Geophysical Year (1957–1958) that permanent research and observation stations were established and thereafter permanently manned in the polar regions. Since then, appreciation has grown not only of the importance of what is occurring in polar regions but also of the associated influences that changes in the Arctic and Antarctic have on mid-latitude weather, the global climate and sea level.

[4] Information on Future Earth is available at http://www.futureearth.org (last access: 25 January 2019).

Reconstructions of past changes in the polar climate make clear that its climate has changed more than the conditions of any other region, ranging from periods when it was warm enough for palm trees to grow on land areas bordering the Arctic Ocean to cold enough that glacial ice that was a few kilometres thick was piled over continental areas so large that the global sea level was pulled down by over 100 m.

As the 20th century proceeded, airline routes were established across the Arctic, the population in high latitudes grew and the potential for extracting resources was recognized. The International Commission on Polar Meteorology (ICPM) was approved in 1963 to focus research attention on high-latitude meteorology. Leading scientists in this field during the early to mid-20th century included, among others, Albert Crary, Joseph Fletcher and Morton Rubin (USA); Svenn Orvig (Norway and Canada); and Norbert Untersteiner (Austria and USA).

With ongoing human-induced warming causing amplified temperature increases in high latitudes, the Arctic's climate is rapidly changing, with sea ice and snow cover retreating, permafrost thawing, and accelerating mass loss from mountain glaciers and the Antarctic and Greenland ice sheets. In addition to affecting mid-latitude weather, polar changes are influencing the Northern Annular Mode and Southern Annular Mode, affecting seasonal to interannual variability. With so much occurring, the importance of improving understanding of polar meteorology and the consequences for the sea level is essential to provide better estimates of emerging impacts having effects around the world.

6.6 International Commission on Dynamical Meteorology

The International Commission on Dynamical Meteorology (ICDM) was approved in 1967. Atmospheric dynamics was an early focus in IAMAS, with a number of experts in this field, including Great Britain's Sir Napier Shaw and Reginald Sutcliffe (most famous for his focus on aviation meteorology, initially for the Royal Air Force activities during World War II), serving as presidents of IAMAS. With model-based weather forecasting starting to be undertaken by many nations in the 1950s and 1960s, improving and extending forecast skill became a major research challenge, especially after Edward Lorenz (USA) in the early 1960s recognized the inherent chaotic results that emerged as a result of seeking to solve the coupled set of nonlinear equations governing atmospheric behaviour (Lorenz, 1963). Leading scientists in early research in this area included Jacob Bjerknes (Norway and USA; no. 17 in Fig. 2); Carl-Gustaf Rossby (Sweden and USA); Alexander Obukhov (USSR); Joseph Smagorinsky, Jule Charney and Norman Phillips (all USA); Aksel Wiin-Nielsen (Denmark); and Sir Brian Hoskins (UK).

Since ICDM's creation, and with substantial efforts by the national meteorological services, the time horizon for skilful model-based weather forecasts has been extended from a few days to 1–2 weeks. Of particular importance in advancing forecast quality has been ensuring a better conditioning of initial conditions (the primary problem in the early modelling effort by Lewis Richardson; no. 11 in Fig. 2), treating the entire global atmosphere, using a finer scale grid (which has also required shortening the time step of the model), implementing less diffusive numerical schemes, better representing subgrid-scale influences and turbulence (treating non-adiabatic processes that were initially not being included), and dealing with the chaotic behaviour caused by the nonlinear equations using an ensemble simulation approach.

With both more extensive observations and better models, there have also been significant advances in the understanding and simulations of not only the global atmosphere but also of the treatment of storms. For example, Schultz et al. (2019) provide a description of how international cooperative activities and exchanges have advanced treatment of extratropical cyclones since the early 20th century. While much attention is given to how the underlying climate is changing, the roles and effects of internal oscillations, ranging from the Madden–Julian Oscillation to Atlantic and Pacific multidecadal oscillations, are currently drawing intense research attention. This is the case both because of how such oscillations affect interannual and interdecadal variations and because of interest in understanding how these oscillations might be influenced by climate change. Improvement of forecast skill at finer spatial scales, nowcasting, better simulation of severe storms and extreme conditions, and greater understanding of apparent cycles and long-term linkages all have the potential to reduce losses of life and improve societal preparation and resilience, so providing exciting challenges for research in dynamical meteorology.

6.7 International Commission on Climate

Climate variations and changes have long been of scientific interest because of how they have affected human activities and played a role in determining the prevailing landscape. In proposing that a change in the atmospheric CO_2 concentration could have been a cause of changes in Earth's climatic history in the 1890s, Arrhenius also hypothesized that human-caused emissions of CO_2 could affect the future climate (Arrhenius, 1896). Fundamental theoretical criticisms of his hypothesis were not resolved by the atmospheric and carbon cycle research communities until the mid-20th century. With the 1960s then becoming relatively cool, recognition that emissions of sulphur dioxide and its conversion to sulphate could also affect the climate broadened inquiry into how the full range of human activities was affecting and could affect past, present and future climates.

The 1970s brought the first analysis of climate change as recorded in ocean-sediment cores (Hays et al., 1976); further studies soon provided records of changes in climate and, through isotopic analyses, the sea level stretching back millions of years. The sediment-core records provided initial confirmation of Serbian geophysicist Milutin Milankovitch's hypothesis from the 1930s that glacial–interglacial cycling was being driven by the combined influences of cyclic changes in the ellipticity of the Earth's orbit, tilt of its axis and precession of the orbit through the seasons (Milankovitch, 1941); studies since then have made clear that many additional processes and feedbacks also play a role (Berger, 2001). Leading climate scientists in the early and mid-20th century included, among others, Hubert H. Lamb (UK); Hermann Flohn (Germany); Mikhail Budyko (USSR); Jacques van Mieghem and André Berger (Belgium); José Peixoto (Portugal); Ye Duzheng (China); and Jerome Namias, Victor Starr, Barry Saltzmann and W. Lawrence Gates (all USA).

To provide a focus for the growing international community of climate researchers, IAMAS established the International Commission on Climate (ICCL) in 1977, with its scope set broadly to include the characteristics, fluctuations and changes in climate on all timescales, covering the past, present and future. Two years later, the first World Climate Conference, organized primarily by WMO (1979), led to establishment of WCRP, which has since then provided a framework for bringing together the research capabilities and interests of individual scientists, organized government agency and laboratory research activities.

In response to concerns regarding ongoing increases in fossil-fuel emissions (e.g. Study of Man's Impact on Climate, 1971; WMO et al., 1985), the Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by WMO and the United Nations Environment Programme (UNEP; later joined by UNESCO's Intergovernmental Oceanographic Commission) with the goal of periodically summarizing and assessing research findings regarding human-driven effects on climate, consequent impacts on the environment and society, and potential technological and policy options for moderating the projected changes in climate. While science typically advances as it seeks to reconcile and resolve unexpected observations and different interpretations among scientists, the IPCC has succeeded in bringing the international scientific community together to assess and summarize both understanding of and uncertainties regarding climate change, its impacts on society and the environment, and approaches and measures for avoiding "dangerous anthropogenic interference with the climate system" (United Nations Framework Convention on Climate Change, 1992). For its accomplishments and its now five assessments[5], carried through with participation of many climate scientists, the IPCC was the co-winner of the 2007 Nobel Peace Prize[6].

With fossil fuels currently providing roughly 80 % of the world's energy and human-induced changes in the climate now pushing the global average temperature toward levels higher than observed in many tens of millions of years, research relating to climate variability and change and integrated impact studies are now the subject of numerous meetings and assessments sponsored not only by IAMAS and other associations within IUGG but also by the WCRP, IPCC, and many other national and international programmes and organizations.

6.8 International Commission on Planetary Atmospheres and their Evolution

Scientific hypothesizing about the climates of Mars and Venus goes back at least to the discovery of the telescope in the early 17th century, with science fiction writers speculating on the potential for alien life during the late 19th and early 20th centuries. The establishment of highly capable observatories and careful spectral analyses provided the first scientific insights into the actual compositions of planetary atmospheres. Within a decade of the launch of the first Earth-orbiting satellite in 1957, fly-by missions took satellites past Earth's neighbouring planets with attempts at landing occurring soon thereafter. These missions provided the basis for improving understanding the energy balances and climates over a much wider range of possible conditions, enriching the types of evaluations of model representations of atmospheric composition and processes and confirming the applicability of physical and chemical relationships for explaining resulting features.

The International Commission on Planetary Atmospheres and their Evolution (ICPAE) was established in 1977, emerging as a result of meetings during the early 1970s of the IRC, which was faced with interpreting satellite-based radiation measurements being taken in planetary fly-bys. The scope of ICPAE was set broadly to include study of planetary, cometary and satellite atmospheres and their evolution (including the Earth's atmosphere, when it is considered in the context of atmospheres on other planets). Significant discoveries have included Venus and Mars hosting liquid water on their surfaces in the past, the extreme greenhouse effect on Venus, the many zonal jet streams in alternating directions on Jupiter and Saturn, erupting volcanoes of many kinds on the planets and their moons, and seasonal extremes on Titan with methane rain filling lakes on the surface. Leading scientists in the early studies of planetary atmospheres included Carl Sagan, Joseph Chamberlain, Thomas Donahue, Seymour Hess, James Kasting, Toby Owen and James Pollack (all USA); Donald Hunten (Canada and USA); Richard Goody (UK and USA); and many others.

In addition to ongoing analytic and Earth-based observational studies, ICPAE members have played leading roles in planetary missions exploring atmospheres in all their diverse

[5]For access to the IPCC assessments and special reports, see https://www.ipcc.ch/reports/ (last access: 25 January 2019).

[6]The award is described at https://www.nobelprize.org/prizes/peace/2007/summary/ (last access: 25 January 2019)

guises, from Pioneer Venus to Venus Express, a multitude of Mars orbiters and landers, and the Voyager Grand Tour of the outer solar system to Galileo and Juno at Jupiter, Cassini at Saturn, and New Horizons' exploration of Pluto's tenuous atmosphere. With the newest satellite-based observatories starting to provide information about the atmospheres of planets orbiting other stars, understanding the compositions and climates of planetary atmospheres and their evolution continues to provide insights into factors that affect the suitability of a planet for supporting life and the types of alterations that might affect this suitability.

6.9 International Commission on the Middle Atmosphere

The International Commission on the Middle Atmosphere (ICMA), originally named the International Commission on Meteorology of the Upper Atmosphere, was approved in 1979. It was formed to provide a focus for international cooperation in research relating to the middle atmosphere, which is considered to reach roughly from the tropopause ($\sim$ 12–18 km, depending on latitude and season) up to the lower thermosphere ($\sim$ 90–95 km). The composition and circulation of the layer are strongly affected by the most energetic radiation emitted by the Sun. Fortunately, the absorption of this energetic radiation by the ozone layer in the middle atmosphere protects the lower atmosphere from much of the biologically damaging UV solar radiation and the consequences of solar storms.

The middle atmosphere's composition is coupled to that of the troposphere via exchanges of trace constituents (e.g. water vapour and methane) and also reflects the tropospheric trends introduced by anthropogenic contributions, notably of carbon dioxide and halocarbons. Middle atmospheric composition is also affected by direct emissions from aircraft and rockets and from the rapid injection of material from the most powerful volcanic eruptions. Trends in trace constituents over the last several decades have been linked to significant trends in stratospheric ozone, including the development of the "ozone hole" over the high southern latitudes in spring. Couplings are also dynamic, with conditions in the middle atmosphere affecting circulation in the troposphere on subseasonal to interannual (and possibly decadal and longer) timescales, especially in the mid-latitudes and high latitudes.

Leading scientists as this field developed during the 20th century included Gordon Dobson and Sydney Chapman (both UK); Michael McIntyre (New Zealand and UK); Alan Brewer (Canada and UK); Taroh Matsuno (Japan); Paul Crutzen (the Netherlands and Germany); Guy Brasseur (Belgium, USA and Germany); Colin Hines (Canada and USA); and James Holton, F. Sherwood Rowland, Richard Lindzen and Susan Solomon (all USA). Major international programmes of relevance to ICMA in the recent past include the Middle Atmosphere Program (MAP; 1982–1985) led by SCOSTEP (Scientific Committee on Solar-Terrestrial Physics) and the SPARC (Stratosphere-troposphere Processes and their Role in Climate) project (1992–present) led by the WCRP.

6.10 International Commission on Atmospheric Electricity

Atmospheric electricity is a field of atmospheric sciences that has a long and rich history, dating back to the time of American diplomat Benjamin Franklin's kite experiment and later to experiments by Lord Kelvin (Scotland and Ireland), Charles T. R. Wilson and Sir George Simpson (both UK), Sir Basil Schonland and D. J. Malan (both South Africa), and, more recently, Bernard Vonnegut and Martin Uman (both USA) among many others. The field deals with the electrical nature of thunderstorms, particularly lightning but also fair-weather electricity, ions and radioactivity in the atmosphere. Lord Kelvin's early interest in the global electrical circuit paved the way for the work at the Carnegie Institution and Wilson's fundamental formative studies (electron runaway, the cloud chamber, global circuit hypothesis, role of electrified shower clouds and electrostatic infrasound) that have many connections with current work.

International meetings under IUGG and IAMAS auspices go back to the mid-20th century, building up a cadre of researchers and providing a forum for expert scientists from around the world. To better focus international collaboration and cooperation, IAMAS approved the International Commission on Atmospheric Electricity (ICAE) in 1989 to supervise, coordinate, and expand upon the conference-organizing efforts of the prior committee that had existed. With the growing dependence on electric power grids, lightning physics and protection has become a key area of interest of ICAE, while in recent years the link between climate change and atmospheric electricity has also received much focus. Members of ICAE were also key in the discovery and understanding of upper-atmospheric transient luminous events (TLEs) such as sprites, elves and terrestrial gamma ray bursts (TGFs).

7 Concluding Remarks

With respect to the organization of scientific research relating to the Earth system, the year 1919 was one of very significant achievement, setting the stage for very significant advances over the succeeding 100 years and beyond. As World War I ended and a serious flu epidemic waned, the rebirth and expansion of international scientific cooperation to its modern scope began. Observational systems were growing in coverage, and scientific understanding of why changes were occurring expanded. Leading scientists of the time showed exceptional foresight in moving to establish the foundation of the international structure that has carried forward scientific advancement in the century since. While much has been learned, the questions for the decades ahead remain as important and daunting as they were 100 years ago, providing a strong and continuing rationale for IAMAS and its 10 commissions to continue to promote international cooperation and advancement.

The IAMAS focus on advancing scientific understanding of the atmosphere has benefited greatly from both active participation of the world community of atmospheric scientists and also from the advances by the broader geosciences community represented within IUGG. With collective gratitude to all who have served and participated in IAMAS over the past 10 decades, IAMAS welcomes all who would join in ongoing and emerging atmospheric and meteorological research. Further information on IAMAS is available at http://www.iamas.org (last access: 25 January 2019).

The multitude of scientific associations, commissions, and similar groupings within and outside of the parenting International Union of Geodesy and Geophysics may appear confusing at times. It reflects, however, the human endeavour to form various cooperating groups and to categorize phenomena arising from the interrelated and transient continua of the solid, liquid and gaseous compartments of the Earth system. Good (2000) reflected in detail about the evolving geophysical scientific disciplines that together form the *union* called IUGG. Upon IUGG's centennial, may this commemorative article contribute further to a common memory and tradition into the future about personalities and groupings that have dealt scientifically with atmospheric issues during the past century.

Data availability. The bulk of information used in this article is taken from the cited references or the currently active websites. In addition, information was drawn from a number of additional sources, including an article by P. H. Shaw in the *Encyclopedia Britannica* (15th edition); early meeting reports appearing in *Science* and *The New York Times*; appropriation bills printed in the *Congressional Record*; and historical information provided on the websites of IAMAS, its commissions and the IUGG.

Author contributions. MCM sought out and assembled much of the historical information in the text and prepared the first and subsequent drafts. HV added to the historical text; participated in revisions of the text; and collected the information in Figs. 1 and 2 and the portraits in Figs. 3 and 4 as well as the contents of Tables 2 and 3.

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Open Access History of Geo- and Space Sciences

IAPSO: tales from the ocean frontier

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Abstract. Our 21st century perspective on the oceans is due to the realization that knowledge of them and specifically their role in earth's climate are central to determining the future health of our planet. This present knowledge of the oceans builds on the farsighted work of people who, over the past century, worked to address seemingly intractable problems. The International Association for the Physical Sciences of the Oceans (IAPSO) has, over that long time span, promoted and supported the international approach that is now commonplace and has championed the provision of cross-cutting activities, the value of which we now fully recognize. This paper describes the key events in IAPSO's history and the roles played by the scientists involved.

1 Introduction

Until about 100 years ago the science of oceanography was primarily the profession of a small number of people, almost all of them men, who devoted their energy and skill, and often their own money, to understand the complicated motion of the sea and the lives of its creatures. In the mid- to late 1700s Benjamin Franklin gave us knowledge of the Gulf Stream and currents off the Atlantic coast of the USA. One hundred years later Matthew Fontaine Maury published *The Physical Geography of the Sea* (Maury, 1855) using data from ships' logbooks that recorded ocean temperature and the speed and direction of winds and currents in the North Atlantic. He also began direct measurements by asking sailors to put messages in bottles, giving the time and location when the bottle was launched and asking the finder to report back to him where and when the bottle was washed ashore. In this way he was able to further refine his charts and maps.

The situation changed with the worldwide voyage of *HMS Challenger* which set out to specifically make systematic measurements of ocean parameters between 1872 and 1876. However, *HMS Challenger* was not the only vessel to be making measurements around this time. Many national vessels including the French naval vessels the *Travailleur* and the *Talisman* and the German *Gazelle* were making biodiversity and hydrographic measurements, and it was after seeing the findings from the two French vessels in an exhibition at the Paris Museum that HMSH Prince Albert I of Monaco made a decision in 1884 to devote his time and resources to oceanography. Having served in the French and Spanish navies as a young man, he had a profound interest in the sea. Over the subsequent 30 years, he financed and used four increasingly impressive research yachts the *Hirondelle, Princesse Alice, Princesse Alice II*, and *Hirondelle II* to make numerous oceanographic measurements, maps and charts. Initially his main collaborators were Baron Jules de Guerne and Jules Richard, and later he was joined by John Young Buchan after he had completed his service as a chemist with the Challenger expedition, where HMSH Prince Albert I also worked with Maurice Leger and Paul Portier to develop scientific equipment. He even used drift bottle measurements like Maury had to determine the splitting of the Gulf Stream, showing one branch heading north towards northern Europe and the other heading south past Spain and Africa before turning back west. His last voyage ended in 1914 with the outbreak of World War I, but he continued to advise military officials on how explosive mines would drift in the ocean and where they would land.

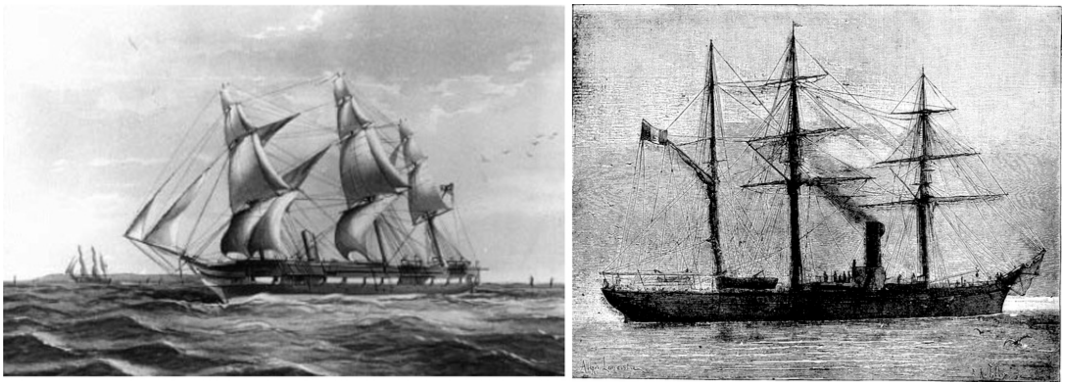


Figure 1. *HMS Challenger* (source: https://en.wikipedia.org/wiki/Challenger_expedition (last access: 19 March 2019) and the French scientific steamer, the *Talisman* (source: https://commons.wikimedia.org/wiki/File:THE-FRENCH-SCIENTIFIC-STEAMER-TALISMAN.png, last access: 19 March 2019).

2 IAPSO history

2.1 In the beginning

As a result of the plethora of ocean measurements being undertaken at the end of the 19th century by individual countries, leading scientists began to advocate the need to pool data and resources for further measurement, to get the best possible understanding – an ideal that has not changed during the last 100 years.

The political arena at the time was very different from what it is today and there was much friction between countries and individual scientists. However, goodwill prevailed and in 1902 the International Council for the Exploration of the Sea (ICES) was established. Its remit was to cover the North Sea, the Baltic Sea, the Norwegian Sea, and the Barents Sea. There had been discussion at a preliminary meeting in 1899 to include measurements in the North Atlantic, supported by the marine stations on oceanic islands such as the São Miguel island in the Azores. It was proposed that these measurements would be combined with the work of HMSH Prince Albert I (Commission Hydrographique Suédoise, 1899). This suggestion was not taken up and the Atlantic investigation was confined to a small region northwest of Scotland. Nevertheless, it was still felt to be imperative for the understanding of the oceanography and fisheries of the marginal seas to have regularly occupied hydrographic stations in the open Atlantic Ocean. It was generally agreed that this was one of the most pressing issues in oceanography. Consequently, following the Ninth International Geographic Congress in 1908, the International Commission for the Scientific Exploration of the Atlantic was established alongside a similar commission for the Mediterranean, and HMSH Prince Albert I of Monaco became the chairman of both commissions.

During the following 2 years the members of the two commissions were selected, and meetings were held in Monaco in 1910 in connection with the inauguration of the Musée Océanographique. At these meetings, detailed plans for a study of the Atlantic were discussed (Berget, 1910). However, the Atlantic Commission did not meet again whereas the Mediterranean Commission (Commission Internationale pour l'Exploration Scientifique de la mer Méditerranée, CIESM) is still in existence.

At the end of World War I, with the encouragement of John Buchan, HMSH Prince Albert I sought to establish an international organization for oceanography. He had always had a strong interest in international cooperation; in 1900, prior to his chairmanship of the Atlantic and Mediterranean commissions, he had granted his patronage to the establishment of the short-lived International Marine Association, the last meeting of which was in 1904. The opportunity arose in July 1919 during the Constitutive Assembly of the newly formed International Research Council when it decided to form the International Union of Geodesy and Geophysics (IUGG) as a union of six sections. One of the sections was assigned to physical oceanography, dealing with tides, currents, temperature, salinity, and other physical phenomena of the oceans, and HMSH Prince Albert I took on the role of its first president. The physical oceanographers did not accept biology being part of their section, but this proved to be of no consequence after HMSH Prince Albert I founded a biological oceanographic section under the umbrella of the International Union of Biological Sciences and became its first president.

2.2 The early years

With HMSH Prince Albert I as president, the applied mathematician Horace Lamb of the UK as vice president, and Giovanni Magrini of Italy as secretary, the Section for Physical Oceanography held its first General Assembly in Paris in 1921. The scope of the section was detailed as follows:

- morphology of the sea bottom,

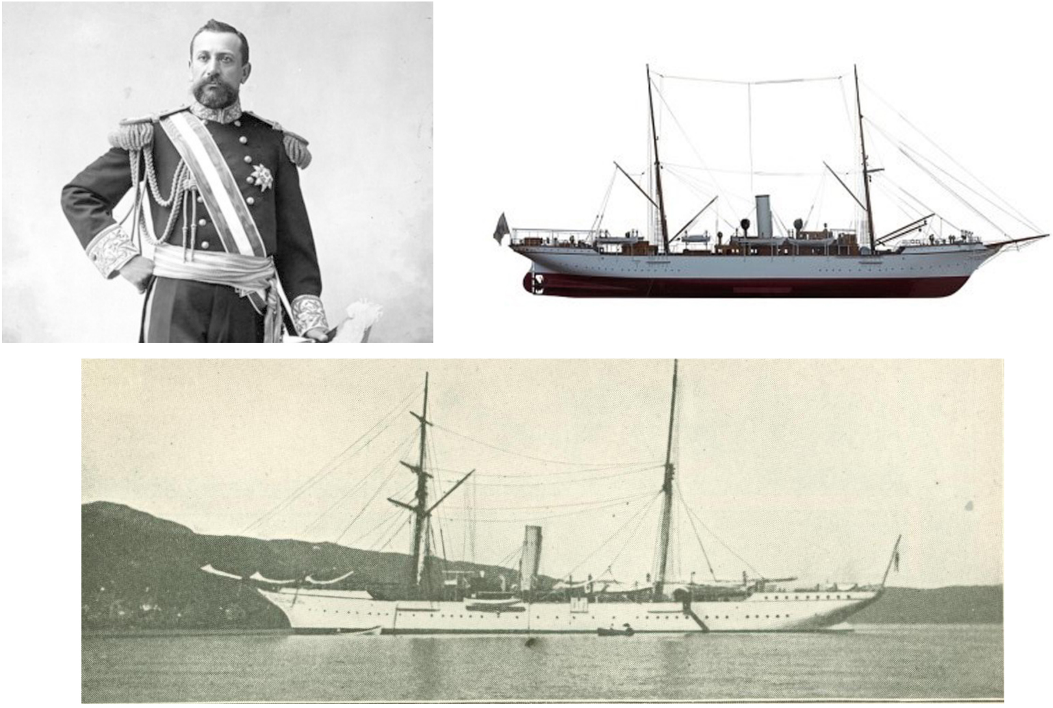


Figure 2. HMSH Prince Albert I of Monaco and his vessels the *Hirondelle* (top; source: http://www.institut-ocean.org/, last access: 19 March 2019) and *Princesse Alice* (bottom; source: http://www.digitalhistoryproject.com/2012/08/prince-albert-of-monaco-as-oceanographer.html, last access: 19 March 2019).

- morphology of the surface of the oceans and seas,
- movements of the water masses, and
- physical and chemical studies of seawater.

Here it was suggested that special committees for the study of the Atlantic Ocean and Pacific Ocean be established, but this was postponed due to concerns over conflicts of interests between countries and scientists (Smed, 2007). In 1921 Otto Pettersson suggested that ICES and the Section for Physical Oceanography regarded each other with dignified reserve "comme deux chiens de porcelaine sur une cheminée"[1] (Pettersson, 1921).

Very soon after the first IUGG assembly held in Rome in May 1922, HMSH Prince Albert I died, and so in July 1922 Vice Admiral Sir John Perry from the UK, who had been elected vice president at the Rome assembly, carried on until the next IUGG General Assembly held in Madrid in 1924. At this time, Odon de Buen of Spain was elected president and Vice Admiral Perry and Magrini continued as vice president and secretary, respectively. However, Vice Admiral Perry died in 1926 and de Buen and Magrini carried on until they were re-elected to their positions at the third IUGG General Assembly held in Prague, Czechoslovakia, in 1927, and Johannes Schmidt of Germany became vice president.

[1]Like two porcelain dogs on a fireplace.

Throughout these years the Atlantic and Pacific special committees had still not been established, but a tidal committee had emerged. In reality, research in the Atlantic was being carried out by ICES, the International Ice Observation and Ice Patrol (forerunner of the US Coast Guard), and the North American Committee on Fishery Investigations. The International Committee on the Chemical and Physical Oceanography of the Pacific, founded in 1923, was responsible for measurements in that ocean.

At an assembly in Seville, Spain, in 1929, held separately from IUGG, the Section for Physical Oceanography adopted the term "Association". This was in line with the proposed reorganization of the International Research Council, which became the International Council of Scientific Unions (ICSU) in 1931. At the fourth IUGG General Assembly held in Stockholm, Sweden, Martin Knudsen of Denmark was elected president, Eugène Fichot of France became vice president, and Rolf Witting of Finland became secretary, while de Buen and Magrini continued as members of the executive committee. At this meeting some preliminary discussions about the Association's statutes and bye-laws began (Procès-Verbaux, 1934), but these were not adopted until 1933, when all the former sections of the IUGG became international associations and were authorized to set up their own statutes.

At the fifth IUGG General Assembly held in Lisbon, Portugal, in 1933, Knudsen and Fichot were re-elected to their positions and Joseph Proudman from the UK became secre-

Figure 3. Professors Harald Sverdrup (source: https://digitaltmuseum.org/011014857601/harald-sverdrup/media?slide=0, last access: 19 March 2019) and Joseph Proudman (source: http://www.tide-and-time.uk/local-heroes-joseph-proudman, last access: 19 March 2019).

tary (he held that position until 1948). Magrini and de Buen continued on the executive committee but Magrini died in 1935. At this assembly it was decided that what was formerly known as the International Association of Physical Oceanography (IAPO) should mainly deal with those parts of oceanography in which mathematics, physics, and chemistry were used for the scientific study of the sea – a situation that continues today. The Atlantic and Pacific committees of the former oceanography section were abolished, but the committee on tides survived.

2.3 The middle years

General assemblies were held in 1936 in Edinburgh, Scotland, and in September 1939 in Washington, D.C. Bjørn Helland-Hansen became president of the Association in 1936 and held that position until 1946 when Harald Sverdrup became president, continuing in that position until 1951.

Due to the disruptions of World War II (WWII), no general assembly was held from 1940 until 1948 when it was in Oslo, Norway. In 1948 Proudman became vice president and Håkon Mosby of Norway became secretary. In 1951 Proudman became president of the Association and had great influence on its development. Back in 1930, he had strongly argued against governmental and non-governmental oceanographic organizations coming together and also against close collaboration between physicists and biologists. He felt that the admission of biologists would cause difficulties and should be avoided in the interest of science. He never changed his opinion – some would say to the detriment of IAPO as we are now acutely aware that some of the big issues such as climate change and ocean acidification cannot be addressed without biologists.

In many ways, WWII was a turning point; the importance of submarine operations and the prediction of conditions on landing beaches provided an impetus that continued into the post-war era and highlighted the inherent variability of the oceans. Since then much more effort has been devoted to marine science. As the science developed, oceanographic institutions were established worldwide and these organizations dealt not only with marine physics, but also with marine chemistry, biology, and geology and geophysics. This resulted in the creation of a Special Committee on Oceanic Research, later to become the Scientific Committee on Oceanic Research (SCOR), in 1957; this coincided with the International Geophysical Year 1957–1958. SCOR became a great success and it is not surprising that there was some friction between IAPO and SCOR.

Historical papers suggest that the General Assembly in Helsinki, Finland, in 1960 was one of note. Subsequent correspondence suggests that the weather was unbearably hot and the venue airless and stifling, causing many either to lose attention or fall asleep as well as divesting themselves of as much clothing as decently possible. Nevertheless, the papers show that at this time IAPO was a thriving organization with committees on tides, sea level, bibliographic classification, chemical oceanography, and the General Bathymetric Chart of the Oceans (GEBCO). The GEBCO committee became one of IAPO's greatest successes. They instigated updated editions of early charts, which had been compiled initially by the Cabinet Scientifique of HMSH Prince Albert I, by working with the International Hydrographic Bureau in obtaining soundings from multiple hydrographic offices worldwide and the World Data Centres, and making decisions about projection, scale, and other parameters. GEBCO continues to this day but under the auspices of the International Hydrographic Organization and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO).

In 1967, IAPO proposed that ICSU integrate all its organizations with an interest in the sea by creating an International Union of Marine Sciences, but this met with opposition, mainly from those who thought that unions should be organized by discipline rather than be interdisciplinary (Charnock, 1984). After much argument the ICSU decided against the proposal and the physical oceanographers changed the name of their Association to the International Association for the Physical Sciences of the Ocean (IAPSO) and broadened its scope to include commissions on marine geophysics and on marine chemistry as well as on physical oceanography. An amicable and constructive arrangement with SCOR was reached, whereby IAPSO continued to provide a forum for international meetings and maintaining standards and methods, and SCOR promoted bottom-up research funding projects and working groups proposed by the research community. The president of IAPSO became an ex-officio member of the SCOR Executive Committee, and over the years subsequent IAPSO presidents have contributed to the running of SCOR and the decisions it makes. In return, many of the IAPSO successes have been in collaboration with SCOR.

In 1970, as IAPSO reached its half century, it held its 15th Scientific Assembly alongside the scientific sessions of SCOR's Joint Oceanographic Assembly in Tokyo. It was arranged by the Science Council of Japan, under the title "The Ocean World". Symposia were organized in cooperation with the International Association of Geochemistry and Cosmochemistry (IAGC), the Scientific Committee on Antarctic Research (SCAR), and the Upper Mantle Committee (UMC). The meeting was also sponsored by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), UNESCO, the World Meteorological Organization (WMO), and the Food and Agriculture Organization of the United Nations (FAO). It was a truly multidisciplinary event with scientific sessions covering all aspects of oceanography.

In 1983, at the General Assembly in Hamburg, IAPSO set up a Commission for Oceanographic Advice to Developing Countries; it later changed its name to the Commission for Oceanographic Cooperation with Developing Countries. It was chaired by Eugene La Fond and one of its first tasks was to organize a workshop entitled Oceanographic Advice to Developing Countries at the General Assembly in 1985 in Vancouver. It also organized another workshop on physical oceanography at the SCOR meeting in Acapulco in 1988. In the hope of fostering marine science in developing countries by improving the quality of scientific papers, the IAPSO Executive Committee approved the commission's suggestion that an award be given for the best scientific presentation by a scientist from a developing country. Gold-coloured medals were cast and two were awarded at the IAPSO Plenary Session of the IUGG General Assembly in Vienna in 1991 to Dindi Satyanarayan and to Ye Longfei, because the two presentations were found to be of equally high quality. These activities started a long-standing commitment by IAPSO to assist scientists in developing countries. Today the Association provides a large number of grants to scientists from these countries.

2.4 Modern IAPSO

The IAPSO that we know today really emerged in 1995. That year IAPSO held its General Assembly in Honolulu in August and it was the largest in the history of IAPSO, involving the greatest number of countries. Led by President Robert Muench, preparations had been in place for over 3 years, including implementation of an up-to-date database of all working oceanographers on the IAPSO mailing list and making the assembly known to them. At the end of this assembly Vere Shannon from South Africa was elected president and Fred Camfield from the USA took over as secretary general, with the title of secretary having changed to secretary general in 1979. During 1996, Camfield established the IAPSO web pages and instigated direct responses to various enquiries received by letter, email, or facsimile. Throughout his time as president, Shannon worked on a strategy document for the Association that was ultimately finalized and distributed in 2004 when some revisions to the statues and bye-laws were made. Shannon was keen to raise the profile of IAPSO and to include more chemistry and biology, so it was agreed that the 2001 assembly would be in Mar del Plata, Argentina, as a joint venture with the International Association for Biological Oceanography (IABO).

Figure 4. Eugene La Fond (source: IAPSO archives).

Figure 5. Paola Malanotte-Rizzoli (source: IAPSO archives).

Following the 1997 assembly the secretary general posted the details and abstracts of the IAPSO symposia and IAPSO-led joint symposia on the website and this has continued to date. It has proved to be a valuable resource to the scientific community with many hits well after the assemblies have finished.

At the end of the IUGG assembly in 1999, Paola Malanotte-Rizzoli became the first female IAPSO president and a chemist, Denise Smythe-Wright, joined the executive committee; representation of this discipline of oceanography had been somewhat short over the years. In addition, the As-

Figure 6. Five recent presidents of IAPSO: Eugene Morozov, Lawrence Mysak, Shiro Imawaki, Paola Malanotte-Rizzoli, and Robin Muench (source: IAPSO archives).

Figure 7. Presentation of the 2017 La Fond Medal to Johnathan Durgadoo (source: IAPSO archives).

sociation changed its name from the International Association for the Physical Sciences of the Ocean to the International Association for the Physical Sciences of the Oceans (plural). It was also decided to instigate a medal award and the suggestion was made that this could be in memory of IAPSO's founder HMSH Prince Albert I.

The joint IAPSO/IABO assembly in 2001 proved to be very successful and a tentative suggestion was made to follow it up in 2005; this resulted in the joint IAPSO/IABO assembly in Cairns, Australia, in 2005, but sadly this example has not been repeated.

In 2007, a decision was made to encourage scientists from developing countries to join the executive committee and it was proposed to separate the duties of treasurer and secretary, which had been combined up until then. Consequently, at the 2007 General Assembly, Johan Rodhe became secretary general and the office moved from the USA to Sweden; Camfield continued as treasurer, a post he relinquished in 2013. Rodhe then went on to completely revise the IAPSO website and also produce publicity material to raise the IAPSO profile with the international community including the production of a pamphlet that was distributed at the 2007 meeting of the American Geophysical Union (AGU) in San Francisco and to worldwide organizations and delegates.

In the last decade, IAPSO has continued to hold biannual assemblies, maintain its commissions and services, and work with SCOR. In July 2015, Rodhe retired from his position as secretary general; the office moved to Italy, managed by the newly elected secretary general Stefania Sparnocchia; and Ken Ridgway from Australia was appointed treasurer.

3 IAPSO awards

In the last 15 years IAPSO has instigated two awards, the Prince Albert I Medal and the Eugene La Fond Medal. These are awarded every 2 years at IAPSO assemblies.

3.1 Prince Albert I Medal

Following the decision in 1999 to instigate a medal in memory of HMSH Prince Albert I, Paola Malanotte-Rizzoli, the IAPSO president at the time, wrote to HMSH Prince Rainier III of Monaco proposing the establishment of an award to recognize the pioneering and extraordinary contributions HMSH Prince Albert I made to and in support of physical oceanography. HMSH Prince Rainier III's answer was enthusiastic; he offered to present a most eminent scientist with a Medal for Excellence in the Physical Sciences of the Oceans. An official protocol was established and ratified by HMSH Prince Rainier III in February 2001. The medal is awarded to a most prominent scientist, chosen by a specially appointed IAPSO Award Committee, in recognition of the scientist's outstanding contributions to the enhancement and advancement of the physical and/or chemical sciences of the oceans.

3.2 The Eugene La Fond Medal

In 2003 the IAPSO Executive Committee decided to award a medal in memory of Eugene La Fond to a scientist born and primarily educated in a developing country. In deference to the 1991 award, it is given to the person who makes the best oral or poster presentation in an IAPSO-sponsored or co-sponsored symposium at an IUGG or IAPSO assembly.

Table 1. IAPSO presidents, secretaries, and secretaries general.

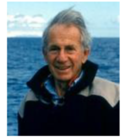
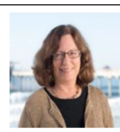
IAPSO presidents	IAPSO secretaries general
1919–1922 S.A.S. Prince Albert I (Monaco)	1919–1930 Giovanni Magrini (Italy)
1924–1930 Odón de Buen (Spain)	
1930–1936 Martin Knudsen (Denmark)	1930–1933 Rolf Witting (Finland) 1933–1948 Joseph Proudman (UK)
1936–1946 Bjørn Helland-Hansen (Norway)	
1946–1951 Harald U. Sverdrup (Norway)	
	1948–1954 Håkon Mosby (Norway)
1951–1954 Joseph Proudman (UK)	
1954–1960 Håkon Mosby (Norway)	1954–1957 Richard H. Fleming (USA)
	1957–1963 Börje Kullenberg (Sweden)
1960–1963 George E. R. Deacon (UK)	
1963–1967 Roger Revelle (USA)	1963–1967 Ilmo Hela (Finland)
1967–1970 Günter Dietrich (F.R. Germany)	1967–1970 Arthur E. Maxwell (USA)
1970–1975 Henri Lacombe (France)	1970–1987 Eugene C. LaFond (USA)
1975–1979 Robert W. Stewart (Canada)	
1979–1983 Devendra Lal (India)	
1983–1987 Wolfgang M. Krauss (F.R. Germany)	
1987–1991 James J. O'Brien (USA)	1987–1995 Robert E. Stevenson (USA)
1991–1995 Robin D. Muench (USA)	
1995–1999 L.Vere Shannon (South Africa)	1995–2007 Fred E. Camfield (USA)
1999–2003 Paola Rizzoli (Italy/USA)	
2003–2007 Shiro Imawaki (Japan)	
2007–2011 Lawrence Mysak (Canada)	2007–2015 Johan Rodhe (Sweden)
2011–2015 Eugene G. Morozov (Russia)	
2015–2019 Denise Smythe-Wright (UK)	2015–2021 Stefania Sparnocchia (Italy)

4 Commissions and services

In fulfilling its role to study the scientific problems relating to the ocean and the interactions taking place at its boundaries, IAPSO has sponsored or co-sponsored many commissions and services, some with IUGG and some with other associations of the IUGG family; these are detailed on the IAPSO website (http://iapso.iugg.org/, last access: 19 March 2019). IAPSO has three current commissions, listed as follows.

- The Joint Committee on the Properties of Seawater (JCS) is a permanent group with limited membership that acts as an international point of contact for questions relating to seawater and maintains a repository of knowledge and software for the scientific community via the website http://www.teos-10.org/ (last access: 19 March 2019). It is jointly sponsored by IAPSO, SCOR, and the International Association for the Properties of Water and Steam (IAPWS) and provides a conduit for communication between its parents and other international organizations such as the Bureau International des Poids et Mesures (BIPM), WMO, and the International Union of Pure and Applied Chemistry (IUPAC). In addition, JSC makes suggestions where gaps exist in available knowledge.
- The Commission on Mean Sea Level and Tides (CMSLT) supports research into applications of sea level measurements. Its membership is open to any researcher with an interest in mean sea level and tides. In addition

Table 2. The Prince Albert I Medal winners to date (source: IAPSO archives).

2001	Walter Munk	for his innumerable contributions to the evolution of physical oceanography	
2003	Klaus Wyrtki	for his ENSO research, developing breakthroughs in understanding and forecasting El Niño, and establishing the tide gauge network that provided the essential oceanographic data set	
2005	Friedrich Schott	for unravelling the basis physics and variability of many key regions of the world's ocean, in particular his description of the circulation of the Indian Ocean	
2007	Russ Davis	for his pioneering development of autonomous platforms for in situ observation, permitting systematic measurements to be made in remote and sparsely observed areas by the international Argo programme	
2009	Harry Bryden	in recognition of his fundamental contributions to understanding the ocean's role in the global climate system	
2011	Trevor McDougall	for his outstanding work on the importance and fundamental problems of ocean fluid dynamics over the full range of ocean sciences and the thermodynamic properties of seawater	
2013	Arnold Gordon	for his outstanding contribution in observational oceanography and in particular for his work in defining the physical processes in the Southern Ocean and Indonesian throughflow	
2015	Toshio Yamagata	for his ground-breaking work and exceptional contribution to our understanding of the El Niño–Southern Oscillation and the newly discovered Indian Ocean Dipole	
2017	Lynne Talley	for her outstanding contribution to our knowledge of the global ocean's water masses, circulation, dynamics, and role in climate	

to sponsoring meetings, the CMSLT is the body responsible for the Permanent Service for Mean Sea Level.

– The Tsunami Commission is responsible for international coordination of tsunami-related meetings, research, and publications. It is a long-standing commission established in 1960 to promote the exchange of scientific and technical information about tsunamis, including an improved understanding of the dynamics of generation, propagation, coastal run-up and the conse-

Table 3. Recipients of the Eugene La Fond Medal to date.

Year	Recipient	Title of presentation
2003	Margarita V. Chikina, Russia	Influence of Mesoscale Circulations on the Coastal Benthic Communities in the Black Sea
2005	Maria del Carmen Grados, Peru	ENSO impacts in the northern boundary of the Humboldt ecosystem during 1960–2005
2007	Catia Motta Domingues, Brazil	Towards more accurate estimates of the thermosteric sea level rise
2009	Bamol A. Sow, Senegal	Simulation of the Senegalese and Mauritanian Upwelling: How are the Winds actually Driving SST Variability and Water Mass Renewal?
2011	Towhida Rashid, Bangladesh	Holocene relative sea level change in Bangladesh
2013	Issufo Halo, Mozambique	Eddy properties in the Mozambique Channel: a comparison between observations and two numerical ocean circulation models
2015	Sana Ben Ismail, Tunisia	Surface circulation features along the Tunisian coast (central Mediterranean Sea): the Atlantic Tunisian current
2017	Jonathan Durgadoo, Mauritius	Indian Ocean sources of Agulhas leakage

quences to society of the tsunami hazard; something that has become particularly relevant in recent years.

IAPSO also has the following two services.

- The Permanent Service for Mean Sea Level (PSMSL) is the internationally recognized global sea level data bank for long-term sea level change information from tide gauges and also provides a wider service to the sea level community.
- The Standard Seawater Service is the only internationally recognized organization for the calibration of salinity measurement devices. Its widespread use over 100 years of IAPSO history has been of great importance to the quality and comparability of salinity data worldwide.

4.1 The Permanent Service for Mean Sea Level

Spatial and temporal changes in mean sea level were discussed at a meeting of IAPO at the 5th General Assembly of the IUGG in Lisbon in 1933. Rolf Witting and Joseph Proudman were the national delegates from Finland and the UK, respectively. Witting was a distinguished Baltic oceanographer and had founded the Finnish Institute of Marine Research in 1918. By 1933, he was also a politician and government minister, and he would go on to be Finnish Foreign Minister in the wartime government.

Witting appreciated the importance of sea level measurements for understanding ocean circulation. In particular, he had an interest in determining the mean dynamic topography of the Baltic Sea by measuring spatial differences between mean sea level recorded at many stations with respect to a common levelling datum (the geoid, in effect). To do that he had to make corrections for glacial isostatic adjustment (then known as post-glacial rebound), which meant that he had to collect time series of relative sea–land levels using tide gauge data.

Proudman had already been active in IAPO for many years. He was nominated secretary of an IUGG Mean Sea Level Committee and set about collecting monthly and annual values of mean sea level using the international contacts of the International Hydrographic Bureau. At an IAPO meeting in 1936, it was decided that the collection should be made available as widely as possible and be published in special volumes. The first such volume was published by Proudman in 1940 as one of the IAPO *Publications Scientifiques* series (IAPO, 1940), and it did not take long for someone to use it to produce the first of many scientific papers on sea level changes using these data (Gutenberg, 1941). In 1951, the terms of reference of the committee were extended to have it report regularly on secular variations in mean sea level around the world.

This brings us to 1958, around the time of the International Geophysical Year. At this point, it was decided that, for several reasons, the Mean Sea Level Committee would be better constituted as a "permanent service" of ICSU. It was considered that having a clearly defined home for the service would provide it with greater financial stability and that the name Permanent Service for Mean Sea Level would provide the necessary international authority. In view of Proudman's close association with the committee, the Tidal Institute of the University of Liverpool, of which Proudman was director, was asked to host it (Rossiter, 1963). Formally, the PSMSL is now a service of the IUGG as a whole: IAPSO provides its main Association link (and the IAPSO Commission on Mean Sea Level and Tides serves as its governing board) while the

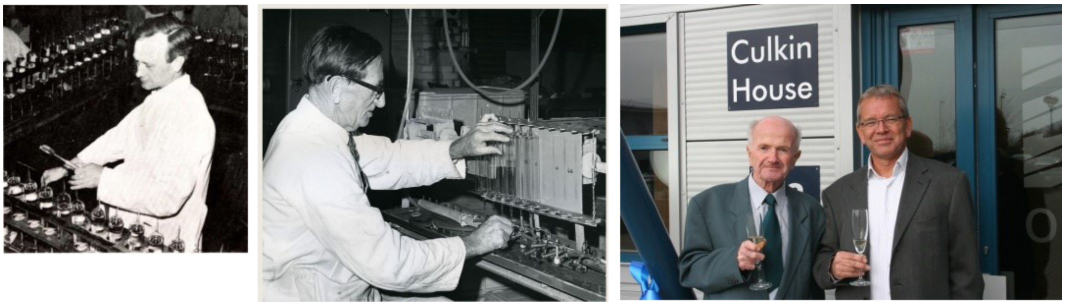


Figure 8. From the early days of Frede Hermann, through IOS to OSIL (source: UK National Oceanography Archives and OSIL).

International Association of Geodesy (IAG) also considers the PSMSL to be one of its services.

As a result of the changes in 1958, the terms of reference of the PSMSL were expanded further. In particular, the service was to encourage the development of a global network of sea level stations and to engage in its own research. Otherwise, the work remained largely the same as that of the committee and has remained so ever since, in spite of many technical developments in data collection, storage, and dissemination. The PSMSL now holds over 70 000 station years of information from around the world with more than 300 records 60 years or longer in the Revised Local Reference subset (stations with datum continuity). The dataset is used by many scientists throughout geophysics, and the provision of those data to users remains the PSMSL's main role.

Between 2012 and 2016, over 330 peer-reviewed papers were published in 97 distinct journals, and the number of citations has increased every year to around 70 citations per year. PSMSL staff also produce their own papers, partly as a means of providing a high-level quality control to the dataset. Papers that make use of PSMSL data are always prominent in the sea-level-related chapters of the research assessments of the Intergovernmental Panel on Climate Change (IPCC).

In recent years, considerable efforts have been put into providing a much-improved website enabling users to find where in the world data exist and the properties of each time series (trends together with uncertainty estimates, anomalies, etc.). In addition, PSMSL is working with other sea level centres to improve data interoperability between data streams and enable closer integration of the mean sea level data set with higher-frequency data. There are also links to records of land movements obtained by Global Navigation Satellite System (GNSS) equipment. PSMSL has started providing data from in situ ocean bottom pressure recorders from all possible sources, fulfilling a remit given to the PSMSL by IAPSO in 1999.

The PSMSL has continued serving the wider sea level community, providing training materials, organizing training courses for developing countries, and playing a major role in the development of the Global Sea Level Observing System (GLOSS) of the IOC of UNESCO. Many more details on the PSMSL's present-day activities can be found on its web site (https://www.psmsl.org/, last access: 19 March 2019) or in publications (e.g. Holgate et al., 2013; Woodworth and Rickards, 2014).

An important point to stress is that, back in 1933, when the original Mean Sea Level Committee was set up, no one knew the uses to which its sea level data would be put many years later. It is clear that a permanent global network of good sea level measuring stations is required, along with the data bank infrastructure to support it such as presently provided by the PSMSL, in order to ensure that future scientists have the data that they need, even if they are not in the applications we think are important now (Nature Geoscience Editorial, 2013).

4.2 The Standard Seawater Service

In the global-scale science of oceanography the challenge of documenting subtle climate-related changes requires well-established and accepted standards. While those for temperature and pressure are universal, marine science has had to establish its own standards for salinity. Thanks to farsighted individuals and to the underpinning support of IAPSO those standards have been maintained for over a century.

By the time IUGG was founded, the concept of salinity had been developed by Scandinavian scientists and the constancy of seawater's chemical composition had been confirmed by Dittmar's analysis of samples from the 1870s *HMS Challenger* expedition (Dittmar, 1884). It was also known that the measurement of the chlorinity of samples, by titration against silver nitrate, could be the basis for determining salinity. By the turn of the century many laboratories were making observations of temperature and salinity, and one of the initial roles of ICES was to coordinate these. ICES recognized that the only practical way to ensure that all salinity measurements were consistent would be to distribute "standard" seawater samples to all researchers. Starting in 1908 Martin Knudsen in Copenhagen assumed responsibility for what became known as the ICES Standard Seawater Service.

And so the service continued to distribute carefully prepared batches of water until Knudsen's retirement in 1947 (at the age of 76). He then concluded that the service needed to be overseen by a well-respected global-scale scientific organization, and so it came about that from 1948 the service became the responsibility of IAPSO.

Standard seawater was produced and distributed from Denmark under first Helge Thomsen's and then Frede Hermann's guidance until 1975 when with IAPSO's support the operation transferred to the UK Institute of Oceanographic Sciences (IOS) under the direction of Fred Culkin (Culkin and Smed, 1979). Shortly thereafter the production and distribution operations of the Standard Seawater Service became a self-sustaining commercial activity, continued from 1989 to the present day by Ocean Scientific International Limited (OSIL; https://osil.com/, last access: 19 March 2019).

IAPSO's links with salinity determination have been firmly rooted in the changing understanding of salinity as a fundamental physical property. In 1978 the concept of salinity moved away from the earlier chemical (chlorinity) basis to one linked to electrical conductivity (PSS-78), and most recently IAPSO-sponsored research has led to the thermodynamically defined Absolute Salinity (Millero et al., 2008).

In the 70 years since IAPSO assumed oversight responsibility for the Standard Seawater Service, marine science has changed beyond recognition – from observational techniques that were established in the late 19th century to the present-day world of robotic recording instruments. Throughout these changes IAPSO's support of this fundamental service to the marine science community has been unswerving.

5 Relationship with SCOR

Each year SCOR approves new working groups (WGs) and the IAPSO Executive Committee is involved in promoting and evaluating the proposals. IAPSO has also co-funded some very successful groups. One of the earliest was WG 10 – Oceanographic Tables and Standards – which became the Joint Panel on Oceanographic Tables and Standards (JPOTS). The recent working groups are listed as follows:

- IAPSO/SCOR Joint Working Group 121 on Ocean Mixing (2002–2004),
- SCOR/LOICZ/IAPSO Working Group 122 on Mechanisms of Sediment Retention in Estuaries (2003–2005),
- SCOR/IAPSO Working Group 127 on Thermodynamics and Equation of State of Seawater (2005–2009),
- SCOR/IAPSO Working Group 129 on Deep Ocean Exchange with the Shelf (DOES) (2006–2008),
- SCOR/IAPSO Working Group 133 OceanScope (2008–2011), and
- SCOR/WCRP/IAPSO Working Group 136 Climatic Importance of the Greater Agulhas System (2009–2012).

Possibly the most successful was WG 127. This was instigated by the IAPSO community and resulted in fundamental changes to the equation of state of seawater as defined by TEOS-10 (TEOS-10, IOC et al., 2010). It involved the introduction of the Gibbs potential function for seawater and a new salinity formulation called Reference Salinity (S_R) expressed in $g\,kg^{-1}$.

Another IAPSO-instigated SCOR working group, the SCOR/WCRP/IAPSO WG 136 – The Climatic Implications of the Greater Agulhas System, organized a conference on The Agulhas system and its role in changing Ocean Circulation, Climate, and Marine Ecosystems. It was held in Stellenbosch, South Africa, in October 2012 and generated a great deal of excitement among participants, particularly among regional scientists, some of whom had not previously attended an international conference.

Over the years there have been a number of joint meetings with SCOR, and in 2017, during the IAPSO/IAMAS/IAGA assembly, IAPSO again joined forces with them to hold a special session for the SCOR/IOC-sponsored IIOE-2 (Second International Indian Ocean Expedition). This proved to be very successful, giving scientists from developing countries who were working in the project the opportunity to apply for IAPSO funding and attend an international conference that perhaps would have otherwise been impossible.

5.1 The equation of state: EOS-80 and TEOS-10

During the 1960s and 1970s traditional sampling techniques, requiring reversing thermometers for temperature measurements, as well as titration-based chemical analyses of water samples for salinity (so-called Chlorinity Salinity or Knudsen Salinity, with units of parts per thousand), were being replaced by newer techniques implemented by electronic instrumentation. These new instruments could be lowered into the ocean or moored to make near-continuous measurements in space or time. However, use of these new technologies raised many technical issues that needed to be solved. One important issue was that new methods for determining salinity and density had to be standardized to supersede old methods first developed in the early part of the 20th century.

Between 1964 and 1980 the Joint Panel on Oceanographic Tables and Standards developed EOS-80. This described (a) the definition of the Practical Salinity Scale 1978, PSS-78 (UNESCO, 1981); and (b) the International Equation of State of Seawater 1980, EOS-80 (UNESCO, 1983). However, EOS-80 did not address several fundamental issues. First, since the EOS-80 algorithms are based on measurements of Standard Seawater, they are not well linked to the actual ocean. It was known even in the 1970s that the densities of real seawater could differ from their EOS-80 calculated values by as much as $0.020\,kg\,m^{-3}$ in the open ocean (Lewis and Perkin, 1978) and that these differences were largest in the North Pacific because of the effects of added nutrients and inorganic carbon (Brewer and Bradshaw,

Figure 9. Members of WG 127 (source: Fig. 10 in Millero, 2010).

1975). Additionally, while thermodynamic relationships can be used to derive certain physical properties from measurements of other properties, the collected algorithms of EOS-80 were thermodynamically inconsistent. In particular sound speed could be derived in two different ways using the EOS-80 algorithms, from different specified correlation equations, with different numerical results.

Consequently in 2005 the SCOR/IAPSO Working Group 127 was established in order to examine the idea of defining seawater properties using a Gibbs function, which would enforce thermodynamic consistency for properties such as sound speed. The stated goal was merely to come up with recommendations in the form of a report and to write some review papers on the matter. At their first meeting in 2006, it was decided to introduce a new salinity variable that had mass fraction units and numerical values that actually reflected the best available estimates for their true values. This was achieved through the development of the Reference Composition and the Absolute Salinity (Millero et al., 2008). In essence the salinity concept was formalized using a carefully defined artificial seawater, which would in practice be most easily realized as a physical artefact by Standard Seawater. The idea that salinity involves a mass of ions and neutral molecules in solution and not the mass of dissolved solids (a distinction that had been poorly understood and/or mostly ignored in the past) was implicit in this process and led to the concept of Reference Composition Salinity. The Reference Composition Salinity is the mass fraction of the constituent inorganic ions and compounds in Reference Composition Seawater, and it can be calculated by summing up the molar concentrations of the constituents of Reference Composition Seawater, multiplied by their atomic weights.

In order to account for composition changes in real seawaters, a correction factor was needed. The eventual choice was to correct Reference Salinity for the composition variations that occur in real seawater by adding to it a Salinity Anomaly to estimate the Absolute Salinity. For Standard Seawater the best currently available estimate of Salinity Anomaly is zero. For real seawater, the Salinity Anomaly is almost always non-zero, and some practical recommendations were made at that time about how the Salinity Anomaly should be defined.

The connections between electrical conductivity, the mass fraction of solutes, and the specific volume of seawater is a very complicated subject, especially so because biogeochemical processes add material to seawater which is inherently less conductive than sea salt, and the chemical equilibria involved depend on temperature and pressure. Consideration of these issues gives rise to several different types of Absolute Salinity, and the connections between them were put on a firm footing by the two papers Pawlowicz (2010) and Pawlowicz et al. (2011), with Wright et al. (2011) being a very readable summary of the issues involved. Since density (or specific volume) is the property of primary interest in physical oceanography, it was decided that the Absolute Salinity of real seawater should be defined to be the mass fraction salinity (on the Reference Composition Scale) of Reference Composition Seawater with the same density as that of the sample being measured at a specified temperature and pressure (Wright et al., 2011). Ongoing research on the meaning and measurement of Absolute Salinity is described in Feistel et al. (2016) and Pawlowicz et al. (2016).

The TEOS-10 (IOC et al., 2010) approach of using thermodynamic potentials to describe the properties of seawater, ice, and moist air means that it is possible to derive many more thermodynamic properties than were available from EOS-80. The seawater properties entropy, internal energy, enthalpy, and particularly potential enthalpy were not available from EOS-80 but are central to accurately calculating the transport of heat in the ocean and hence the air–sea heat flux in the coupled climate system. The incorporation of the spatial and temporal variations of the relative composition of sea salt means that the baroclinic ocean transports can be evaluated more accurately than was possible by using only Practical Salinity.

6 IAPSO and societal issues

Over the years, several of IAPSO's activities have underpinned the climate projections of IPCC. In particular, IAPSO's support of work on sea level have made major contributions to all of the IPCC research assessments. Without the Standard Seawater Service to assure the precision of salinity measurements, the detection of subtle basin-wide changes as indicators of changes in the earth's hydrological cycle would not be possible. More recently the outcomes of working groups on ocean mixing and TEOS-10 have influenced the climate models used in the IPCC's 5th assessment in 2014 and continue to influence oceanography worldwide.

In addition, in November 2015, the IUGG secretary general Alik Ismail-Zadeh suggested to the president of IAPSO,

Figure 10. Presentation of the 2017 Prince Albert I Medal to Professor Lynne Talley (source: IAPSO archives).

Figure 11. The IIOE-2 ECS meeting in Cape Town (source: IAPSO archives).

Denise Smythe-Wright, that she instigate an initiative in response to the marine science issues raised by the Group of Seven (G7) science ministers in the communiqué arising from their meeting in October 2015. The G7 countries have outstanding oceanographic capabilities and are well placed not only to continue to provide world leadership in marine environmental research, but also to use the research outcomes for their wider socio-economic benefit. Realizing that this was not just an IAPSO initiative, the president of IAPSO approached Peter Burkill, president of SCOR at the time, and together they mustered 14 international experts to address the following issues: marine litter, ocean acidification, biodiversity loss, deoxygenation, ocean warming, ecosystem degradation, and deep-sea mining. This became the ad hoc IUGG/IAPSO/SCOR working group of experts on the Future of the Ocean and its Seas (2015–2016), which resulted in the report *Future of the Ocean and its Seas: a non-governmental scientific perspective on seven marine research issues of G7 interest* (Williamson et al., 2016). It was submitted to the G7 science ministers prior to their meeting in Japan, in May 2016.

7 The future

Back in 1975, there was some discussion about the benefit and future of the "Big Meeting" and such discussion continue today. However, IAPSO believes that the free and easy atmosphere of IAPSO assemblies, whether in conjunction with other associations or during the IUGG general assemblies, still provides the best possible environment for scientific discussion and the bringing together of ideas. In the 1970s IAPSO was very mindful of the growth of oceanography due to the explosion in technical development, resulting in a wealth of data and the idea that oceanography was one of the fastest-growing areas of science. We now have a plethora of autonomous systems and vehicles and so oceanography is again riding high. In its 100 years IAPSO has become the organization for oceanographic standards and services and with the growth in new systems there is now more than ever a need for calibration and inter-comparison, and IAPSO's aim for the future is to build on its reputation and take this aspect of its work forward. This does not mean we will lose sight of our biannual assemblies or funding for workshops and in support of scientists from developing countries.

As the Association approaches it centenary, it is interesting to note that it is no longer a male-dominated organization. The second female president, Denise Smythe-Wright, was appointed in 2015 and 5 out of 11 of the 2015–2019 executive committee members are female; in 2017 IAPSO had its first female Prince Albert I Medal winner – Lynne Talley. Our sights are now looking to encourage young scientists into the Association, and in the last year we have set up our Early Career Scientists network (ECS) and instigated Early Career Scientist medals which will be awarded for the first time in 2019. We believe we are well placed to face the next 100 years.

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The International Association of Geodesy: from an ideal sphere to an irregular body subjected to global change

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Abstract. The history of geodesy can be traced back to Thales of Miletus (∼ 600 BC), who developed the concept of geometry, i.e. the measurement of the Earth. Eratosthenes (276–195 BC) recognized the Earth as a sphere and determined its radius. In the 18th century, Isaac Newton postulated an ellipsoidal figure due to the Earth's rotation, and the French Academy of Sciences organized two expeditions to Lapland and the Viceroyalty of Peru to determine the different curvatures of the Earth at the pole and the Equator. The Prussian General Johann Jacob Baeyer (1794–1885) initiated the international arc measurement to observe the irregular figure of the Earth given by an equipotential surface of the gravity field. This led to the foundation of the International Geodetic Association, which was transferred in 1919 to the Section of Geodesy of the International Union of Geodesy and Geophysics. This paper presents the activities from 1919 to 2019, characterized by a continuous broadening from geometric to gravimetric observations, from exclusive solid Earth parameters to atmospheric and hydrospheric effects, and from static to dynamic models. At present, we identify geodesy as the discipline of quantifying global change by geodetic measurements.

1 Introduction: historical background

Geodesy, the discipline of measuring and representing the Earth's surface, is one of the oldest sciences (e.g. Torge and Müller, 2012). Thales of Miletus (∼ 624–546 BC) developed the concepts of geometry, i.e. the measurement of the Earth, which he regarded as a disk floating on the oceans, and Pythagoras of Samos (∼ 580–500 BC) considered the Earth an ideal sphere levitating in space. Aristotle (384–322 BC) defined geodesy as the practical application of geometry, and Eratosthenes of Cyrene (276–195 BC) was the first to estimate the radius of a spherical Earth by astronomic and geodetic observations (Fig. 1).

Claudius Ptolemy (∼ 100–160 AD) realized a geocentric world system by a catalogue of about 6300 locations with geographic coordinates (Kleineberg et al., 2011) and depicted them on maps. This system was valid until the end of the Middle Ages, when Nicolaus Copernicus (1473–1543) proposed the heliocentric system with a spherical Earth in an elliptical orbit around the Sun. Isaac Newton (1643–1727) raised the discussion on the figure of the Earth again by his physical model of an ellipsoid as the equilibrium figure of a rotating Earth, i.e. a flattening of the Earth at its rotation poles. Measurements of the differing curvatures of the meridian at the North Pole (Lapland, 1736–1737) and the Equator (Viceroyalty of Peru, 1735–1744) performed by the French Academy of Sciences (Fig. 2, left) confirmed this model.

In the following decades there was considerable activity observing the curvature of meridians (i.e. the deflection of the vertical ε, Fig. 2, right) in many geographic locations. Astronomic observations at the end points (a and b or c and d, respectively) of the meridian arc provide the natural latitude difference $\Delta\Phi$; geodetic triangulation yields the latitude difference $\Delta\varphi$ on the ellipsoid. The difference $\varepsilon = \Delta\Phi - \Delta\varphi$ is the so-called deflection of the vertical, which shows significant differences in varying regions. Carl Friedrich Gauss (1777–1855) concluded that this is due to the geographically varying gravity of the Earth, and that the true figure of the Earth is given by the ocean under calm conditions (without tides, currents etc.). Gauss' student Johann Benedict Listing

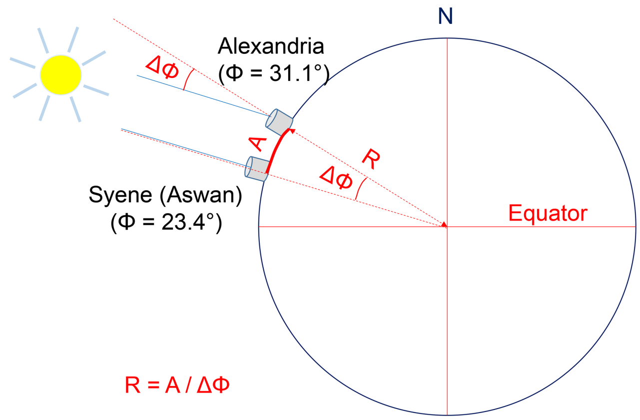

Figure 1. Eratosthenes' method of determining the radius of a spherical Earth. At the summer solstices the Sun is mirrored in a water supply well in Syene (today's Aswan High Dam), but in Alexandria, located on the same meridian, the Sun is casting a shadow with a length corresponding to an angle of $\Delta\Phi = 7.7°$, i.e. the latitude difference between both locations. Measuring the distance from Alexandria to Syene (arc A) yields the Earth's radius $R = A/\Delta\Phi$.

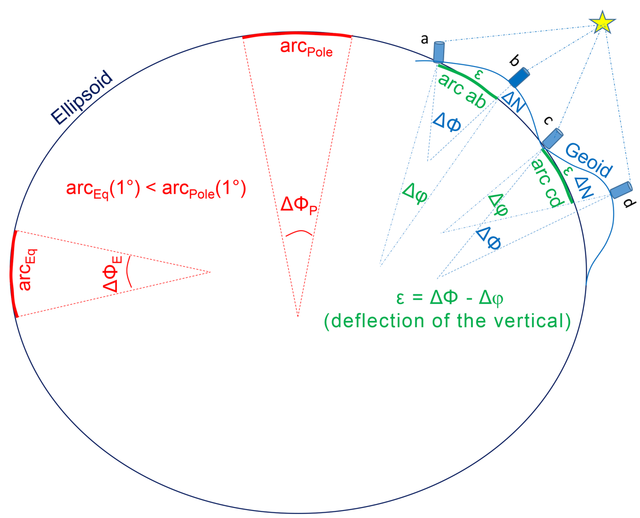

Figure 2. Determination of the flattening of the ellipsoid (left) and the varying curvature of the meridian (right) from astronomic ($\Delta\Phi$) and geodetic (ellipsoidal $\Delta\varphi$) meridian arc measurements showing different deflections of the vertical ε and geoid heights N.

(1808–1882) called the corresponding surface the "geoid". Geoid height differences (ΔN) result from multiplying the deflection of the vertical by the arc length. The determination of the geoid became a fundamental challenge of geodesy, as it is till the present, because all concepts related to water surfaces (oceans, lakes, rivers, and channels, down to water-level bubbles for levelling the geodetic instruments) and the physical heights orient themselves to the geoid.

Johann Jacob Baeyer (1794–1885) wrote a memorandum "On the size and figure of the Earth" (Baeyer, 1861) as motivation for a project for the "Central European arc measurement". By the end of 1862, 15 states had signed an intergovernmental agreement and an association was formally established at the General Conference in Berlin 1864. IUGG's International Association of Geodesy (IAG) considers these years to be its origin (Helmert, 1913; Tardi, 1963; Torge, 2016). The association was extended to all of Europe in 1867 and to the worldwide "Internationale Erdmessung" (International Geodetic Association) in 1886. The intergovernmental convention was renewed every 10 years; however, at the end of 1916 it expired because of World War I.

2 Transition to the IUGG Section of Geodesy

In 1917, the President of the International Geodetic Association, Léon Bassot, and the Director of the Central Bureau, Friedrich Robert Helmert, passed away. The Vice-President, Oskar Backlund, had died in 1916. Two persons guaranteed the continuation of the geodetic activities by proposing the "International Geodetic Association of Neutral Nations": Raoul Gautier (Switzerland, 1854–1931) as the new President and Hendricus Gerardus van de Sande Bakhuyzen (the Netherlands, 1839–1923) as the Secretary since 1900. Six states (Denmark, the Netherlands, Norway, Spain, Sweden, and Switzerland) and the Central Bureau in Potsdam, Germany, continued the administration, measurements, and data analyses, in particular those of the International Latitude Service, from 1917 to 1921, despite the war (Krüger, 1922; Levallois, 1980; Torge, 2005).

In January 1918, the French geodesist Charles Lallemand (1857–1938) sent a draft convention for a new international geodetic association to the delegates of the former association. He denounced the self-styled Association of Neutral Nations and the continued activity of the Central Bureau in Germany, and pushed for the exclusion of the former German and Austro-Hungarian empires (Levallois, 1980). Raoul Gautier objected judiciously, correcting some exaggerations, but the draft formed finally the basis of discussion at the conferences in London and Paris in 1918 that led to the foundation of the International Union of Geodesy and Geophysics (IUGG) with the Section of Geodesy in Brussels 1919. This Union included only allied and neutral nations of World War I (Angus-Leppan, 1984).

The IUGG constituent assembly in Brussels 1919 appointed Charles Lallemand President of the new Union, and William Bowie (1872–1940), the USA representative to the International Geodetic Association, President of the Section of Geodesy. The French Geodesist Georges Perrier (1873–1946), experienced in international cooperation in African, American, and European (Balkan) countries (Perrier, 1923), and very active in the preparation of the assembly (Boucher and Willis, 2016), was appointed the Section's Secretary General. These appointments were temporary, to be confirmed at the first General Assembly.

The IUGG Section of Geodesy held its constituent assembly during the first IUGG General Assembly from 4 to 9 May 1922 in Rome. Fifty-nine delegates represented 23 countries (Europe 15, Africa 1, Asia 1, Australia 1, North America 3, and South America 2). There were seven half-day sessions dealing with (I) administrative and organizational topics, (II) national reports, (III) scientific issues, and (IV) international operations.

Administrational and organizational themes defined the basics of the Section. These were the following.

1. The statutes and organization of the Section, which were entrusted to a commission.

2. The Vice-President of the Section with the election of Raoul Gautier, former President of the previous International Geodetic Association of Neutral Nations.

3. Financial issues, where the Secretary General George Perrier explained the financing via the IUGG membership fees of the countries, as it continues until the present.

4. Publications, with the decision to create a geodetic bulletin (Bulletin Géodésique) for periodic publications, including the proceedings (Comptes Rendus) of the general assemblies. This serial exists to today, renamed the *Journal of Geodesy*.

5. The maintenance of international services, such as the International Latitude Service, which was established in 1899 by the International Geodetic Association.

6. Proposed activities of the Section were identified:

   - observations and theories on the deflections of the vertical,
   - gravity intensity (on land and sea),
   - isostasy,
   - Earth tides,
   - shape of the geoid, and
   - stability of the Earth in time.

National reports to the General Assembly were published in another series, the Travaux de la Section de Géodésie. The first issue started with a report on the activities of the International Geodetic Association from 1912 to 1922 (van de Sande Bakhuyzen, 1923), followed by the reports of the participating countries. This publication series continues until the present, changed from national reports to the reports of the IAG components.

Scientific issues focussed on international rules and definitions for

- fixing the density and precision of triangulation points, baselines, astronomic coordinates, etc.;
- minimum details to be included in publications of different works;
- choice of an international reference ellipsoid;
- choice of a unique map projection system;
- lines to follow or regions to explore for the geoid and gravity anomalies' determination; and
- a bibliography of geodesy.

International operations dealt in general with the connection of triangulation networks in different countries to be organized by the Section, e.g. in Belgium and France, Sardinia and Liguria, Cairo and Europe. This was in principle a continuation of the work initiated by the Central European Arc Measurement in 1862, and continued until 1921.

3 IUGG Section of Geodesy between the World Wars (1922–1939)

The structure of the Section of Geodesy for the first period 1922–1924 was based upon 10 rapporteurs for the essential geodetic problems at that time: triangulation and bases, precise levelling, geodetic astronomy, deflections of the vertical, gravity intensity, isostasy, latitude variation, projections, Earth tides, and stability of the Earth in time. Two commissions were established to study (1) the general requirements of geodetic research and (2) the publication of primary values of the trigonometric lines, which were originally given in different units, in the decimal system. Two permanent commissions on latitudes and longitudes were set up in cooperation with the new International Astronomical Union (IAU), the International Latitude Service (ILS) of the International Geodetic Association (since 1899), and the Bureau International de l'Heure (BIH) established in 1912 (Guinot, 2000).

At the General Assembly in Madrid 1924, the Section's Statutes were adopted defining the decision-making, administrative, and scientific structure. These were

- the Bureau, composed of the elected President, Vice-President, and Secretary General,
- the Secretariat, responsible for correspondents, budget, publications, archives, etc.,
- the Executive Committee, composed of the Bureau and four elected members,
- the Permanent Commission, composed of one delegate of each member country,
- the General Assembly, composed of all the delegates of the member countries, and
- the Scientific Commissions performing the Section's geodetic activities.

One of the most important decisions for science and practice was the adoption of the Hayford spheroid as the International Reference Ellipsoid 1924. Important innovations were the gravity meters on land (spring gravimeters) and at sea (Vening-Meinesz pendulum). Eighteen commissions were set up in 1924 and continued until 1933, and with small modifications until 1946. Table 1 lists those commissions. There were also two joint commissions together with the Section of Physical Oceanography on variations of the mean sea level, and the Sections of Seismology and Volcanology on studies of the Earth's crust.

Besides the modifications in the Commission's structure, there was a change in the officers of the Section in 1933. William Bowie was elected IUGG President and Raoul Gautier had passed away in 1931. The Section elected Felix A. Vening-Meinesz as the new President and Walter D. Lambert as Vice-President. George Perrier continued as the Secretary General. The Washington 1939 General Assembly started 3 days after the beginning of World War II. The programme was substantially changed and reduced, and the scheduled elections were suspended. The organizational status remained thus until 1946. The officers are listed at https://iag.dgfi.tum.de/en/iag-history-photos-of-the-presidents-and-secretaries/ (last access: 15 February 2019).

4 The re-establishment of the International Association of Geodesy after World War II

Immediately after the end of World War II, in December 1945, the IUGG Executive Committee met in Oxford to discuss the continuation of the Union and convened an extraordinary General Assembly in Cambridge, in July 1946. The IUGG Section of Geodesy had been renamed the "International Association of Geodesy (IAG)", and its Permanent Commission met in August 1946. The Secretary General George Perrier had died in February 1946, and Pierre Tardi was elected as his successor. The principal decision of the meeting was to establish a general scientific structure composed of five Sections. The General Assembly in Oslo 1948 ratified these Sections, which remained until 1963:

- Section I: Triangulations;
- Section II: Precise Levelling;
- Section III: Geodetic Astronomy;
- Section IV: Gravimetry;
- Section V: Geoid.

Section I dealt with the activities started in the early years of international cooperation in geodesy and carried out by the IUGG Section of Geodesy since 1922, i.e. the connection of national networks. A first important project after World War II was the Réseau Européen de Triangulation (RETrig). The US Army Map Service (AMS) ordered in 1947 the creation of a unified net in Europe and realized it initially by the European Datum 1950 (ED50). The IAG was reluctant to work on a military project; however, a resolution at the General Assembly in Brussels 1951 advocated a scientific continuation. A challenge was the use of the upcoming electronic and electro-optic distance measurements superseding the triangulation baselines and leading to trilateration. Another major topic was the reduction of the observations to the ellipsoid, i.e. the requirement for orthometric heights and geoid models. The availability of the first electronic calculators encouraged the development of novel adjustment procedures.

The focus of precise levelling was the analysis of systematic errors, in particular caused by the atmospheric refraction, and referring the surface measurements to the geoid through a gravity reduction process. These topics were of special importance for the connection of national levelling networks. European countries decided in 1955 to establish a unified European levelling network (Réseau Européen Unifié de Nivellement, REUN) and to use geopotential numbers instead of orthometric or dynamic heights. The first connections of neighbouring national networks showed significant discrepancies, which led to the detection of different mean sea levels at the reference tide gauges. A preliminary list of such offsets was presented at the General Assembly in Toronto 1957.

The geodetic astronomy discussion concentrated on different instruments and methods of latitude, longitude, and azimuth determination. The major error source arising from time transfer could be improved by using oscillography; i.e. the time signal was recorded in order to trace irregularities. Results of measurements with a new instrument, the zenith camera, showed promising results for simultaneous determination of latitude and longitude. Section III planned with the ILS a special activity for observing polar motion in the framework of the International Geophysical Year 1957/58, in cooperation with other astronomical, geophysical, and meteorological unions and associations. At the General Assembly in Helsinki 1960 there was for the first time a discussion on using artificial satellites instead of celestial bodies.

Gravimetry had referred since 1909 to the Potsdam absolute pendulum measurements (Potsdam Gravity System). Connecting observations at Washington and London-Teddington with the Potsdam Observatory had already shown in the 1930s significant discrepancies. Free-fall measurements in Paris-Sèvres, Leningrad, and Ottawa from 1952 to 1958 confirmed these deviations. Many countries installed calibration lines for adjusting their gravimeters. In order to cover the entire Earth's surface, gravity measurements at sea and in the air were advanced. The Bureau Gravimetrique International (BGI) has collected these data since 1951.

Classical geoid determination is restricted to regional computations using the astro-geodetic techniques combining deflections of the vertical derived from astronomical obser-

Table 1. Commissions active in the period from 1924 to 1939.

Commission name	Comments
Finances	
Original values of trigonometric lines in decimal system	1933 renamed Bibliography
The Invar	1933 renamed Triangulation
Intensity of gravity	1933 split into land and sea
Latitudes	
Longitudes	
Projections	
Tides of the Earth crust	
Problems also of interest for Seismology and Volcanology	1927 discontinued
International regulation of geodetic works	1933 discontinued
Examine the establishment of topographic and oceanic maps	1933 discontinued
Junction of Belgian and French triangulations	
Junction of French and Italian triangulations	1933 discontinued
Junction of triangulations of Sardinia, Liguria and Corsica	1933 discontinued
Junction of Spanish and French triangulations to Morocco	
Junction of the Meridian arc of Capetown via Cairo to Europe	
The Meridian arc from the arctic ocean to the Mediterranean	
The Meridian arc traversing Siam and neighbouring countries	
Precise levelling	established 1930
Time	established 1933
Arc of a mean parallel	established 1933
Study of a joint adjustment of the European network	established 1933
Notations	established 1936
Geoid	established 1936

vations with triangulation results (see Fig. 2). Discussions on this method continued in Section V until more and more gravity observations became available. Heiskanen published in 1957 a global geoid using all available gravity data in a grid of 6679 geographic $1^\circ \times 1^\circ$ blocks (Fig. 3). Discussions focussed on the applied methods, e.g. Stokes' integral, spherical harmonics, and least squares collocation.

5 The inception of the space age in geodesy (1963–1983)

The General Assembly in Berkeley 1963 adopted a fundamental change in the IAG structure due to the launch of artificial satellites for geodetic applications. In particular, the NASA balloon satellites provided epoch-making results, as they enabled for the first time direct intercontinental observations for point positioning with a considerable impact on the classical methods of triangulation and geodetic astronomy. With more and more precise geodetic observations, changes in the geometry of the Earth's surface could be measured, at first in the vertical direction. Consequently, the structure of the IAG Sections required change from the Triangulations Section to the more general Geodetic Positioning Section, adding artificial satellites to Section III, augmenting the Levelling Section with the topic of Crustal Motion, and broadening the Geoid Section to Physical Geodesy. The new structure comprised

– Section I: Geodetic Positioning;

– Section II: Levelling and Crustal Motion;

– Section III: Geodetic Astronomy and Artificial Satellites;

– Section IV: Gravimetry; and

– Section V: Physical Geodesy.

Geodetic Positioning continued with the adjustment of continental triangulation networks, now more concentrating on electronic distance measurements via trilateration. The error analyses and methods of adjustment were major research topics. Observations of artificial satellites were limited in the decade of the 1960s to those based on geometric methods, for example, satellite triangulation based on photographs of the 30 to 40 m diameter balloon satellites ECHO I (launched 1960), ECHO II (1964), and PAGEOS (1966) against the background of stars. Continental- and global-scale networks were observed.

As repeated levellings demonstrated significant height changes, countries started re-measuring their national levelling networks and interpreting the variations with respect to vertical motions of the Earth's crust. The Commission on Recent Crustal Movements (CRCM), established in 1960, collected these data and published maps of observed height changes.

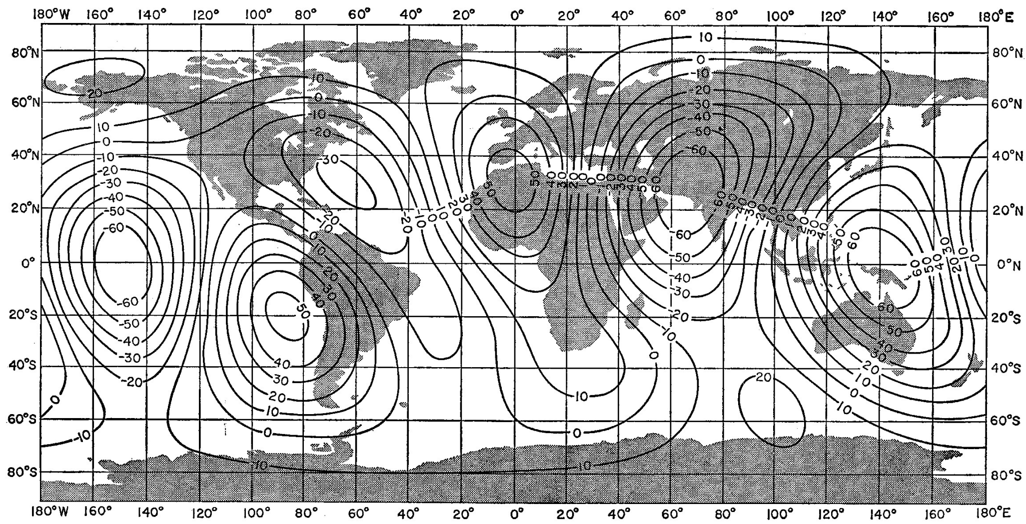

Figure 3. The Columbus geoid (Heiskanen, 1957).

Astronomical activities continued with latitude and longitude observations in cooperation with the ILS, which changed its name to the International Polar Motion Service (IPMS) in 1962. During the 1960s the most significant result in the use of artificial satellites was global satellite triangulation. International partners established cameras around the globe and placed the photographic plates at the disposal of various analysis centres. The result was a global network of 45 station positions with accuracies from ± 2 to 8 m (Fig. 4).

The main activity in gravimetry in the 1960s was the observation of the global gravity network with absolute (pendulum) and relative (spring gravimeter) measurements. Many calibration lines served for standardizing the gravimeter scales. The International Gravity Standardization Net 1971 (IGSN 71) was the result of a common adjustment of observations over 17 years.

The Physical Geodesy Section dealt with theoretical and numerical studies on the geometry and gravity field of the Earth. A primary result was the Geodetic Reference System 1967 (GRS 67) defining the fundamental conventional parameters of the Earth: the semi-major axis a, the dynamical form factor J_2, the geocentric gravitational constant GM, and the angular velocity of the Earth's rotation ω.

At the General Assembly in Moscow 1971, there was another change in the structure of sections, giving more emphasis to and broadening of space techniques and its applications:

– Section I: Control Surveys;

– Section II: Space Techniques;

– Section III: Gravimetry;

– Section IV: Theory and Evaluation;

– Section V: Physical Interpretation.

Levelling was subsumed into the Control Surveys Section, and the principal fields of study persisted in adjustments of triangulation/trilateration and levelling networks, with a focus on the specific challenges of atmospheric refraction and least squares adjustment.

Space techniques concentrated on the satellite Doppler and laser technologies, and laser ranging to the moon was commenced. There were Doppler observation campaigns in all the continents during the 1970s, yielding a precision at the decimetre level, i.e. 1 order of magnitude better than optical satellite triangulation. At the start of the 1980s, the global laser ranging network provided station coordinates at the centimetre level (Fig. 5, Christodoulidis et al., 1984).

Gravimetry concentrated on absolute gravity meters, in particular the transportable free-fall and symmetric rise-and-fall instruments. The precision increased significantly during the 1970s. Precise repeated relative measurements showed significant gravity variations in tectonically active regions (such as Iceland and the South American Andes). Marine gravimetry was improved and extended over all the oceans.

The newly established Section on Theory and Evaluation studied mathematical methods in geometric and gravimetric (particularly in electronic) data processing. The necessity for a reliable Geodetic Reference System led to the revision of the GRS 1967 and the release of the updated GRS 80, which is still valid.

The Physical Interpretation Section aimed to model geophysical parameters from geodetic observations with special interest in solid Earth tides, geoid and gravity anomalies, recent crustal movements, and mean sea level (jointly with the International Association for the Physical Sciences of the Oceans, IAPSO).

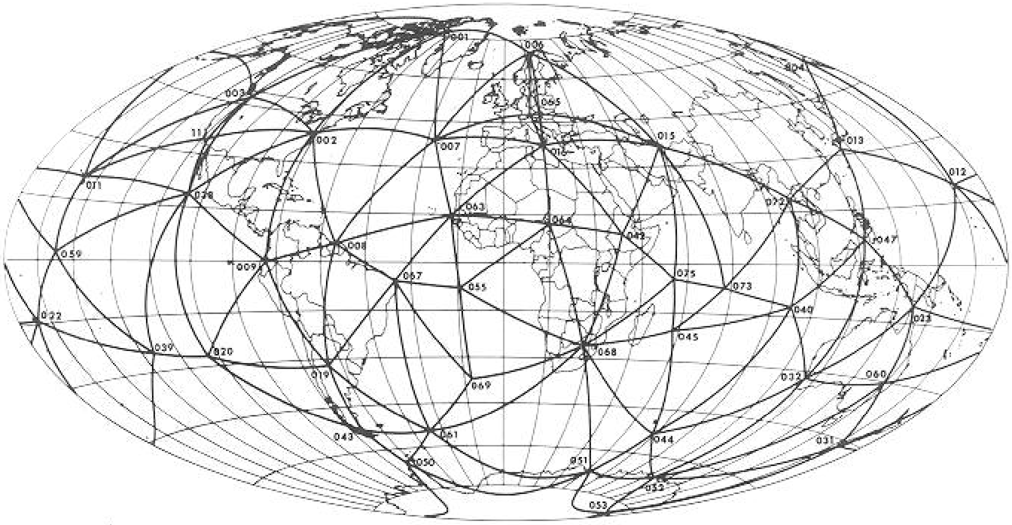

Figure 4. Global network based on satellite triangulation with an accuracy of ±2–8 m (Schmid, 1974).

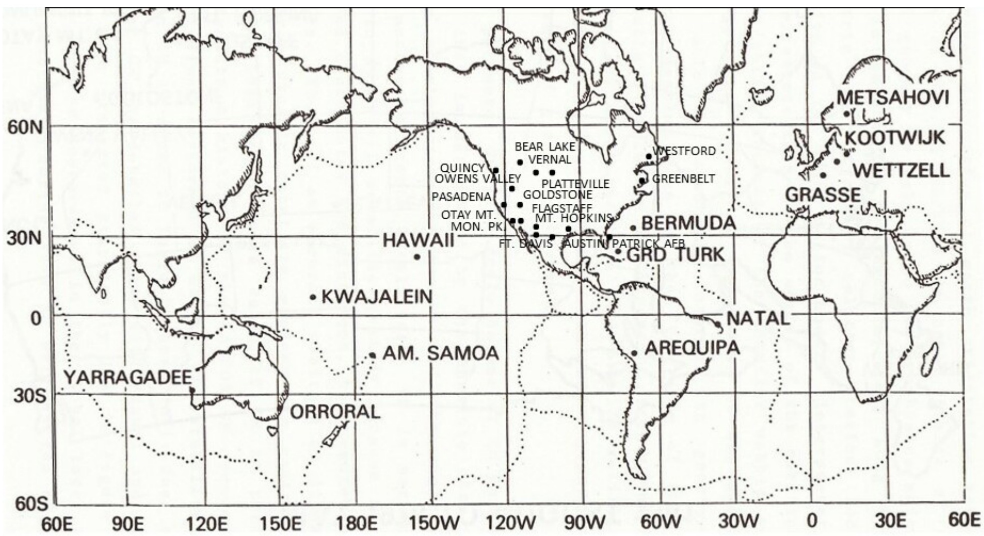

Figure 5. Satellite laser ranging network in the early 1980s (Christodoulidis et al., 1984).

6 Geodynamic research with geodetic techniques and IAG Services (1983–2003)

The IAG structure adopted at the General Assembly in Hamburg 1983 was substantially a specification of the sections' names, with the research fields remaining in essence as before:

- Section I: Positioning;
- Section II: Advanced Space Technology;
- Section III: Determination of the Gravity Field;
- Section IV: General Theory and Methodology;
- Section V: Geodynamics.

Section I continued studies on triangulation and levelling, and their applications in its Commission X, "Continental Networks", with sub-commissions established for all continents. Study Groups investigated network design, inertial techniques, and atmospheric effects. Satellite positioning was initially integrated into Section II. GPS theoretical studies started in Section I in 1983, its application for continental GPS networks in 1987 in its Commission X.

The geodetic space techniques and its applications were treated in Section II, in particular in its Commission VIII, "Coordination of Space Techniques for Geodesy and Geodynamics" (CSTG). It started with Doppler campaigns, followed by satellite laser ranging (SLR), very long baseline interferometry (VLBI), and the Global Positioning System

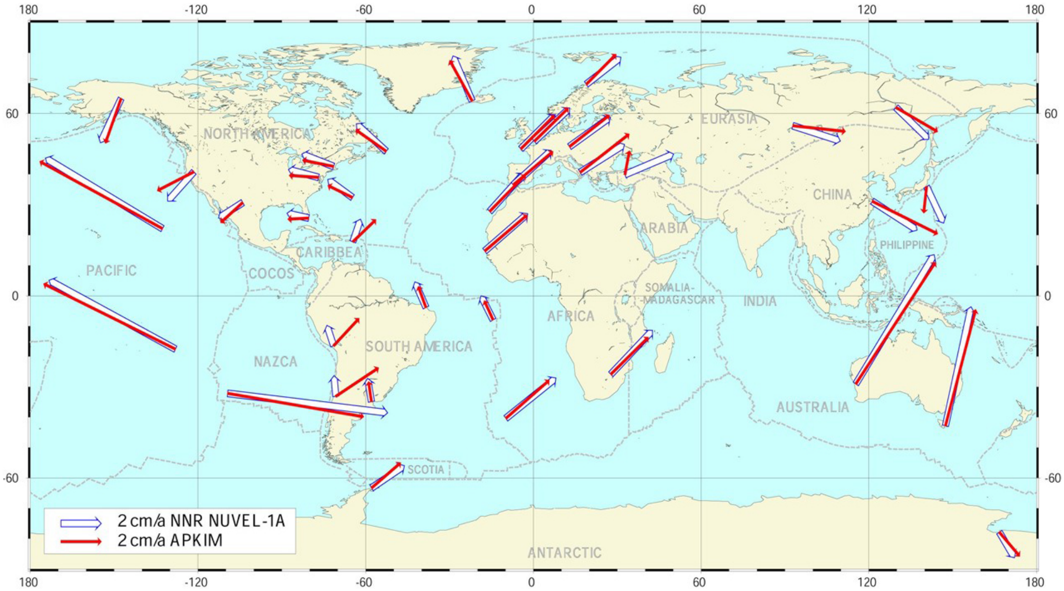

Figure 6. Comparison of actual plate kinematic models (APKIMs) from geodetic observations with a geophysical plate motion model (NNR-NUVEL-1A) derived from observations over millions of years (Drewes, 1998).

(GPS). IAG International Services for these techniques (Table 2) were initiated by the CSTG (Beutler, 2000).

Section III expanded from terrestrial gravimetry, now concentrating on absolute gravimeters, to global gravity field determination including airborne and space measurements. The International Geoid Service (IGeS) was established in 1991 to collect and analyse regional geoid computations. Many study groups investigated specific modelling problems.

Studies of the general theory and methodology of geodetic techniques and parameter estimation focussed on space techniques with respect to the boundary value problem, gravity field modelling, differential geometry, relativity, wave propagation, and transformations.

The geodynamic phenomena were traditionally Earth rotation and tides. The International Centre for Earth Tides (ICET), International Polar Motion Service (IPMS), and Bureau International de l'Heure (BIH) were consequently affiliated with Section V. Other services were the Permanent Service for Mean Sea Level (PSMSL), the International Centre on Recent Crustal Movements (ICRCM), and the Global Geodynamics Project (GGP).

The IAG Services collected and analysed a range of measurement types, and estimated corresponding parameters. An example of recent crustal movements is the comparison of geophysical and geodetic models of tectonic plate motions (Fig. 6). The IPMS and BIH merged in 1987 to become the International Earth Rotation and Reference Systems Service (IERS), which took over the task of combining results of the geometric space techniques (SLR, VLBI, GPS, DORIS) previously done by the BIH. The first International Terrestrial Reference Frame (ITRF), computed from these data, was released in 1988.

7 The Global Geodetic Observing System (2003–2019)

A new IAG structure was adopted at the General Assembly in Sapporo 2003 (Beutler et al., 2004). The Sections, which included Commissions, Special Commissions, Special Study Groups, Working Groups, and Services, were restructured into Commissions and Services, and theory was concentrated in an Inter-Commission Committee. The Global Geodetic Observing System (GGOS) is coordinating products of the above-mentioned components:

- Commission 1: Reference Frames;
- Commission 2: Gravity Field;
- Commission 3: Earth Rotation and Geodynamics;
- Commission 4: Positioning and Applications;
- Inter-Commission Committee on Theory (ICCT);
- Global Geodetic Observing System (GGOS).

Reference frames form the basis for all geodetic parameters. Station coordinates and their changes in time (i.e. their velocities) are computed as multi-year solutions incorporating technique-specific solutions from the IAG Services in close cooperation with the IERS. The latest result is shown in Fig. 7.

Table 2. IAG Scientific Services (Status 2018).

Name	Year	Principal geodetic products
Bureau International des Poids et Mesures (BIPM)	1875	Metre convention, time parameters
Permanent Service of Mean Sea Level (PSMSL)	1933	Sea level heights at tide gauges
Bureau Gravimétrique International (BGI)	1951	Gravity values from terrestrial data
Int. Earth Rotation & Reference Systems Service (IERS)	1987	ILS/IPMS (1899/1962), BIH (1912)
International Service for the Geoid (ISG)	1991	Regional geoid models
International GNSS Service (IGS)	1994	Satellite orbits, clocks, coordinates
International Laser Ranging Service (ILRS)	1998	Geocentric station coordinates
International Digital Elevation Model Service (IDEMS)	1999	Digital terrestrial elevation models
Intern. VLBI Service for Geodesy & Astrometry (IVS)	1999	Earth orientation, rotation, coordinates
International DORIS Service (IDS)	2003	Doppler satellite orbits, coordinates
International Centre for Global Earth Models (ICGEM)	2003	Compare global gravity models
International Gravity Field Service (IGFS)	2004	Coordinate gravity field products
Intern. Geodynamics and Earth Tide Service (IGETS)	2016	ICET (1956), GGP (1997)

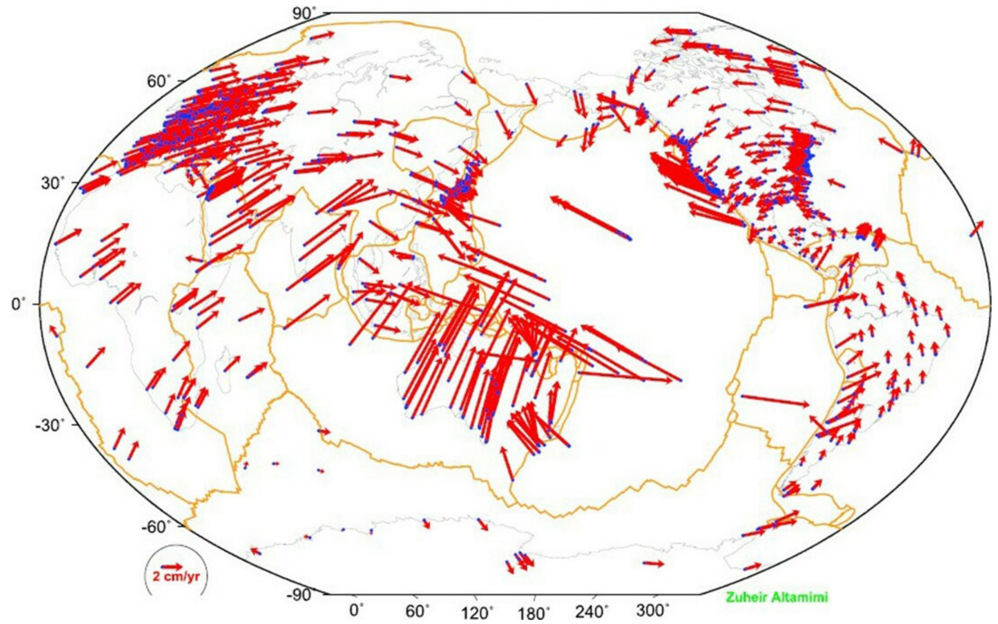

Figure 7. Station velocities of ITRF2014 (Altamimi et al., 2016).

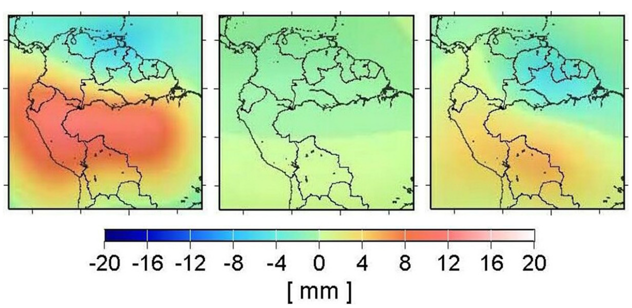

Figure 8. Geoid heights from 10-day solutions of GRACE observations in May (wet season, left), September (dry season, middle), and December (right) 2003 (Schmidt et al., 2006).

The Gravity Field Commission studies terrestrial, marine, airborne, and space observations and computes static and time-dependent global and regional gravity field models in close cooperation with the Global Gravity Field Service (IGFS). Figure 8 shows an example of temporal regional geoid variations due to hydrologic effects in the Amazon region.

Earth rotation includes the time-dependent Earth orientation in space (precession/nutation, Universal Time) and relative to the Earth's body (polar motion). Deformations include plate tectonic motions (cf. Fig. 6), crustal deformations, and sea surface variations. The studies are carried out in cooperation with the IAG Services and the International Astronomical Union (IAU).

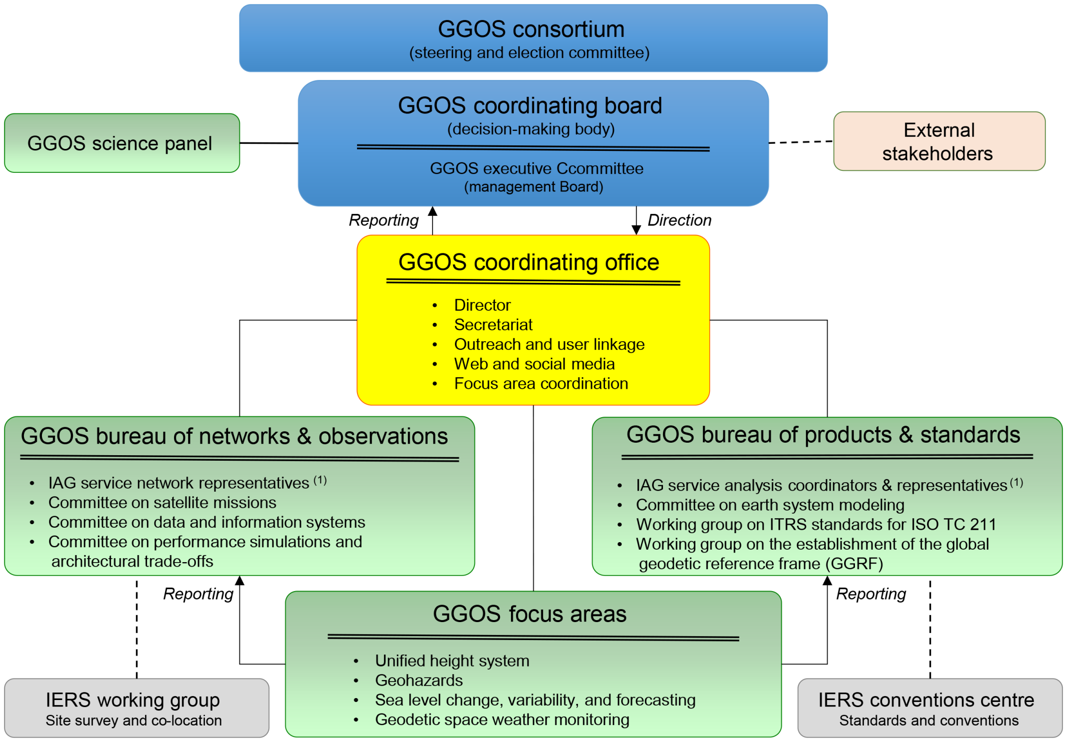

Figure 9. Structure of IAG's Global Geodetic Observing System (GGOS).

Geodetic positioning is applied in many disciplines, e.g. navigation, engineering, topography, and atmosphere remote sensing. Commission 4 studies the techniques (such as GNSS, remote sensing, or unmanned aerial vehicles – UAV) and the modelling in close cooperation with the corresponding IUGG Associations and external societies (in particular the International Federation of Surveyors, FIG).

ICCT acts as the international focus for theoretical geodesy, monitoring developments in geodetic methodology and encouraging the study of mathematical and physical problems in all fields of geodesy by means of Joint Study Groups with the Commissions and Services.

GGOS is the flagship of IAG, established to monitor the geodetic and geodynamic properties of the Earth as a system in cooperation with the Commissions and Services (Beutler et al., 2005). Its mission is

- to provide the observations needed to monitor, map, and understand changes in the Earth's shape, rotation, and mass distribution;
- to provide the global geodetic frame of reference that is the fundamental backbone for measuring and consistently interpreting key global change processes and for many other scientific and societal applications; and
- to benefit science and society by providing the foundation upon which advances in Earth and planetary system science and applications are built.

An overview of the GGOS structure is presented in Fig. 9.

8 Conclusion and outlook

Geodesy has changed dramatically during the latest century, which is mainly due to three extraordinary developments:

1. the advent of artificial satellites and its geodetic applications;
2. the very precise measurement of time (all modern geometric and gravimetric measurements are based on travel time measurements); and
3. the evolving information technology to process the large amount of data generated by geodetic techniques. Here, modern AI technologies offer interesting perspectives to handle the rapidly growing number of monitoring data.

The challenge to the IAG is using these achievements for the reliable measurement and representation of global change parameters. Future work shall concentrate on new satellite technologies and concepts (mini and micro satellites), quantum technology, new sensors, and micro-electro-mechanical systems (MEMS). The first steps in this direction are written in a strategy discussion of the IAG Executive Committee, which will be presented at the General Assembly in Montreal, July 2019.

Detailed descriptions of IAG activities are published in the quadrennial Geodesist's Handbook and the biannual IAG Reports (Travaux de l'AIG), both available at https://iag.dgfi.tum.de (last access: 15 February 2019). A summary of the IAG administrative history is given in Drewes and Adam (2016).

Data availability. There are original data used in this paper. It is a historical report. If results are cited, they are based on data of the cited literature.

Competing interests. The authors declare that they have no conflict of interest.

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IAGA: a major role in understanding our magnetic planet

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Abstract. Throughout the International Union of Geodesy and Geophysics's (IUGG's) centennial anniversary, the International Association of Geomagnetism and Aeronomy is holding a series of activities to underline the ground-breaking facts in the area of geomagnetism and aeronomy. Over 100 years, the history of these research fields is rich, and here we present a short tour through some of the International Association of Geomagnetism and Aeronomy's (IAGA's) major achievements. Starting with the scientific landscape before IAGA, through its foundation until the present, we review the research and achievements considering its complexity and variability, from geodynamo up to the Sun and outer space. While a number of the achievements were accomplished with direct IAGA involvement, the others represent the most important benchmarks of geomagnetism and aeronomy studies. In summary, IAGA is an important and active association with a long and rich history and prospective future.

1 Introduction

The International Association of Geomagnetism and Aeronomy (IAGA, Association Internationale de Géomagnétisme et d'Aéronomie – AIGA) is one of the eight associations of the International Union of Geodesy and Geophysics (IUGG). It is a non-governmental body funded through the subscriptions paid to IUGG by its Member Countries. IAGA is concerned with the understanding and knowledge that result from studies of the magnetic and electrical properties of the Earth's core, mantle and crust, the middle and upper atmosphere, the ionosphere and the magnetosphere, the Sun, the solar wind, the planets and interplanetary bodies. IAGA has a long history and can trace its origin to the Commission for Terrestrial Magnetism and Atmospheric Electricity, part of the International Meteorological Organisation (IMO), which was established in 1873. Following World War I, the International Research Council was established, and at meetings in London and Paris in 1918, the IUGG (Union Geodesique et Geophysique Internationale in French) was formed, with "Terrestrial Magnetism and Electricity (Magnétisme et Electricité Terrestres)" as section D, with leadership given to IMO. At the First IUGG General Assembly (Rome in 1922), the Section of Terrestrial Magnetism and Electricity became one of the constituent sections of the union. During the IVth IUGG General Assembly (Stockholm in 1930), the sections became associations, one of them being the International Association of Terrestrial Magnetism and Electricity (IATME). In 1951, the upper atmosphere scientists expressed their interest in being recognized in IATME. It was Sydney Chapman who suggested using "geomagnetism" instead of "terrestrial magnetism" and who created the term "aeronomy", explained as "the science of the upper atmospheric regions where dissociation and ionization are important". In 1954, again in Rome, during the 20th IUGG General Assembly, the newly created association adopted its present name, the International Association of Geomagnetism and Aeronomy. For more details on the history of IAGA, the reader is referred to a comprehensive review by Fukushima (1995).

Since 2015, IAGA has been organized into six divisions and four inter-divisional commissions, each led by a chair and a co-chair. Each division may form working groups in given specialized topics, and elects officers to run the business of the working groups. The working groups are the elementary cells of the association and at that level the main scientific activities of IAGA are designed. Division I deals with the theory of planetary magnetic fields, paleomagnetism, and rock and environmental magnetism. Division II aims at improving the understanding of the dynamics, chemistry, energetics and electrodynamics of the atmosphere–ionosphere system as well as the coupling processes. Division III is focused on understanding how energy input from the Sun and solar wind influence and drive Earth's magnetosphere and upper atmosphere. Division IV represents research fields related to solar wind, the heliosphere, and solar magnetism. Division V deals with quality standards in geomagnetic data acquisition, observatory and survey procedures, geomagnetic indices, data dissemination, and analyses of magnetic data for the purpose of understanding the various sources of the magnetic field. Finally, activities of Division VI involve the investigation of all theoretical and practical aspects of the spatial distribution of electrical properties within the Earth's and planetary interiors. Four inter-division commissions (on developing countries, history, education and outreach, and space weather) complete the internal IAGA structure. Moreover, IAGA is involved in several union and inter-association activities. The current activities of IAGA are due to efforts made during decades and even centuries by researchers involved in the Earth's magnetism, aeronomy and solar magnetic field. The breadth and complexity of research carried out within IAGA was reflected in five volumes of the IAGA Special Sopron Book Series published by Springer.

Besides the scientific activities, IAGA also plays a major role in the exchange and dissemination of scientific information between the various scientific communities in developing countries. The Interdivisional Commission on Developing Countries aims to increase the participation of developing countries in IAGA activities. Notable are the IAGA efforts for early career scientists. Since 2013, IAGA has organized the "IAGA School" (Fig. 1) during the week before the IAGA Scientific Assemblies and the IUGG General Assemblies with the aim of providing excellent early career scientists with a good basic understanding of a wide range of the scientific topics covered by IAGA. The IAGA-sponsored participants include the recipients of the IAGA Young Scientist Awards, and a number of PhD students or young postdocs, who are nominated by the IAGA Divisions and Working Groups. The Interdivisional Commission on Education and Outreach is deeply involved in these activities.

The current structure of IAGA is presented at http://www.iaga-aiga.org/ (last access: 18 January 2019). On the same website, information on how IAGA is administered by an Executive Committee on behalf of IUGG Member Countries, in accordance with the Association's Statutes and By-Laws, can be found. The website provides a wide range of information about the association's activities, from the meetings, products and services to awards and honors. The full list of IAGA resolutions is also available, as well as all IAGA Newsletters.

The IAGA Presidents and Secretaries General have been pioneers and well-known scientists in the modern world of geomagnetism and aeronomy, e.g. Aikitsu Tanakadate (Fig. 2). The full list of those who served IAGA can be found on the IAGA website. However, we have to mention here two other great names: Sydney Chapman, who acted as President of the International Association of Meteorology and Atmospheric Sciences (IAMAS) from 1936 to 1948, President of IAGA from 1948 to 1951, President of IUGG from 1951 to 1954, and President of the Special Committee for the International Geophysical Year, and Valery Troitskaya from the Soviet Union, who was the first woman president of any IUGG association (IAGA President between 1971 and 1975).

Figure 1. Participants of the first IAGA School, held in Merida, Mexico, in 2013, during the trip to inland Yucatan cenotas.

In order to acknowledge significant scientific achievements as well as service to the community, IAGA presents several medals and awards. The most prestigious is the Shen Kuo Award, introduced in 2006 (IAGA News 43). Outstanding long-term service to the IAGA community in technical or managerial positions is acknowledged by the Long Service Award (introduced in 1988, IAGA News 27). The Young Scientist Award (introduced in 2005, IAGA News 43) is addressed to young scientists for outstanding contributions at meetings and workshops for which IAGA is a major sponsor. Finally, since 1980 (IAGA News 19), a person who has given outstanding service to IAGA may be elected an Honorary Member of IAGA.

Information on the IAGA activities has been published regularly since 1966 through the annual IAGA News (Fig. 3; all issues of the IAGA News are available on the IAGA website). The following statement can be found in the first issue of the IAGA News: "One should express a wish that all the investigators carrying on this work publish the information quickly. This would give an opportunity to coordinate the work, made by different investigators in different countries in a better way." The role of IAGA is clearly noted.

During the last century IAGA provided official (via resolutions) and organizational support to several high-profile scientific programmes, including the Second International Polar Year (IPY) in 1932–1933, the International Geophysical Year (IGY) in 1957–1958, the International Years of the Quiet Sun (IQSY) in 1964–1965, and more recently, two international efforts in 2007–2008 to commemorate the 50th anniversary

Figure 2. Aikitsu Tanakadate (1856–1952, Japan), the first President of IAGA, who measured the Earth's gravity and magnetic fields across Japan and established a latitude observatory in Mizusawa in 1899.

of the IGY: International Heliophysical Year (IHY) and Electronic Geophysical Year (eGY).

In the following, the scientific landscape of the association is reviewed from its foundation until the present. The review is complicated by the diverse studies carried out within IAGA (from geodynamo up to the Sun and outer space), as well as a huge number of facts and achievements, either accomplished with IAGA involvement, or representing the most important benchmarks of geomagnetism studies. Therefore, in this paper, only a flavor of the IAGA heritage is presented.

2 Geomagnetic landscape before IAGA

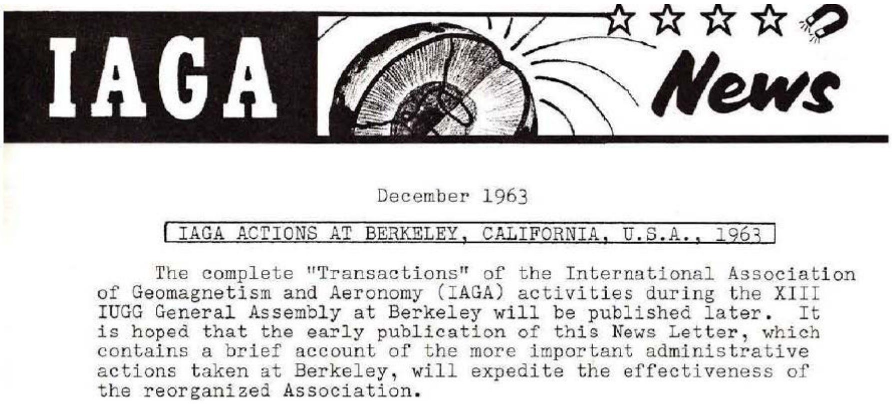
The history of IAGA is linked to the history of the Earth's magnetic field, the origin of it being the most challenging scientific question for many centuries. In fact, Albert Einstein once ranked the source of the Earth's magnetism among the most important unsolved problems in classical physics.

The magnetic compass was used already in the 4th century BC in China. However, the magnetic declination, denoting the difference between the magnetic and geographic north, was first recognized by Shen Kuo in 1088 (to recognize this notable person, IAGA named its highest award after him). In Europe, one of the first key names in geomagnetism remains Pierre de Maricourt, known as Petrus Peregrinus ("the pilgrim"). In his "Epistola de Magnete", written in 1269 and translated into English during the 20th century (Arnold, 1904), de Maricourt describes the pivoted compass he carefully devised and the concept of magnetic poles.

At the beginning of the 17th century a debate on local versus global departures of the field from that of an axial dipole pitted William Gilbert (with his "De Magnete", published in 1600) against Guillaume le Nautonier (with his "Mecometrie de l'eymant", published in 1601), as shown in Mandea and Mayaud (2004). Gilbert's work resolved long-lasting discussion and experiments concerning magnetism and measurements by the magnetic needle, and magnetism became the first property to be attributed to the body of the Earth as a whole. During this century, the number of measurements of magnetic directional elements increased. The Royal Society in London and the Académie des Sciences in Paris supported the building of astronomical observatories and also fostered magnetic research.

At the end of the 17th and the beginning of the 18th centuries, significant progress was made in the fields of electricity and magnetism. One of the major discoveries to be recalled, relevant to some areas of geomagnetism, was associated with the activity of Edmund Halley, the leader of the first global magnetic survey (1698–1700) on the Paramore (e.g. Thrower, 1981). The classical charts of lines of equal values of declination obtained during the survey (in 1701 for the Atlantic and in 1702 for the world) are still relevant. The first half of the next century paved the way from laboratory instruments to magnetic observatories. Von Humboldt, Gauss and Weber were deeply involved in running observatories, which formed the Göttingen Magnetic Union (Magnetischer Verein). As early as in 1836, Gauss advocated measuring the full magnetic vector and not only directional values. In the same epoch, the simultaneity of magnetic disturbances over large areas was confirmed, and Gauss developed his general theory of geomagnetism and showed that almost all of the magnetic field observed at the Earth's surface originated inside the Earth (Gauss, 1839).

The number of highlights to be traced back to the 18th and 19th centuries is large, and it is far beyond the scope of this work to name all of them. The interested reader is referred to Courtillot and le Mouel (2007), Gubbins and Herrero-Bervera (2007), and Cliver and Petrovsky (2019). In the following, we focus on a few of the achievements of the scientists from the IAGA community, in order to highlight the importance of the magnetic field observation and modelling, as well as processes linked to the origin of the Earth's magnetic field and solar–terrestrial relationship.



IAGA News

December 1963

IAGA ACTIONS AT BERKELEY, CALIFORNIA, U.S.A., 1963

The complete "Transactions" of the International Association of Geomagnetism and Aeronomy (IAGA) activities during the XIII IUGG General Assembly at Berkeley will be published later. It is hoped that the early publication of this News Letter, which contains a brief account of the more important administrative actions taken at Berkeley, will expedite the effectiveness of the reorganized Association.

Figure 3. The first issue of the IAGA News.

3 Earth's magnetic field – role of observations and theory

3.1 Magnetic observatories

Since the time of Gauss, the number of geomagnetic observatories has grown to about 200, partly due to international efforts such as the International Polar Year in 1882–1883, the Second International Polar Year in 1932–1933 and the International Geophysical Year in 1957–1958. Important steps in establishing the global network of cooperating digital magnetic observatories, including adoption of modern standard specifications for measuring and recording equipment, have been accomplished by Division V. The role of observatories was and still is essential in monitoring the variations of the geomagnetic field, both for science and for commercial and governmental usages.

To facilitate the work at observatories, several IAGA guides for observatory practice were written over the years (Wienert, 1970; Jankowsky and Sucksdorff, 1996; and the dedicated chapters in Mandea and Korte, 2011). The nature of the observatory work has changed considerably over the years. Currently, the observatories produce their data in digital form. New techniques in instrumentation have made it possible to automate part of the observatory work and to increase the absolute accuracy of the data. This is crucial, because the new era with global magnetic surveys using satellites needs very ground-based accurate observatory data.

The effort to produce highly accurate data is complemented by their dissemination (through platforms such as Worlds Data Service (WDS) or INTERMAGNET). This started a half-century ago, with the proposal made by Sydney Chapman (Fig. 4).

3.2 Magnetic satellites

During the International Geophysical Year, the Soviet Union stunned the world with the launch of Sputnik, the first satellite ever; this tiny sphere with a radio transmitter was launched on 4 October 1957. The first spacecraft carrying a magnetometer was Sputnik 3, launched in May 1958. Twelve on-board instruments provided data on pressure and composition of the upper atmosphere, magnetic and electrostatic fields, concentration of charged particles, photons and heavy nuclei in cosmic rays. Following the Russian achievements, the NASA series of the POGO (Polar Orbiting Geophysical Observatory) and the OGO (Orbiting Geophysical Observatories) 2, 4, and 6 satellites carried out global measurements of the scalar field from October 1965 through June 1971. The first detailed magnetic observations of the Earth were performed by the MAGSAT (1979–1980), followed by Oersted (1999–2013[1]), SAC-C (2000–2013), CHAMP (2000–2010), and Swarm (2013–), all carrying vector and absolute magnetometers. All IAGA divisions are involved and take advantage of the exceptional datasets provided by space magnetic missions.

Division I of IAGA plays an important role in planetary magnetism. Magnetometers were taken to the Moon during the later Apollo missions. The lunar magnetic field was also extensively observed by several spacecraft launched by different nations. Over the last decades, spacecraft have visited nearly all of the large bodies in the solar system, measuring their magnetic fields, as well as those of the Sun (by remote sensing) and the interplanetary magnetic field. Without naming all of them, let us recall that many spacecraft have visited Mars since the Soviet Union first launched Mars 1 in 1962. However, Mars did not relinquish its secrets until the Mars Global Surveyor spacecraft orbited this planet in 1997, demonstrating that it does not have a global magnetic field of internal origin, but that its crust is intensely magne-

[1] In 2018 Oersted is still in orbit, however without ground connection.

III SELECTED ITEMS OF INTEREST

THE WORLD MAGNETIC ARCHIVE. Some notes on its purpose and progress by Sydney Chapman

Development of the WMA Proposal

Since October 1967 I have been trying to have made available in machine readable form the hourly values of the magnetic elements from the great store of reliable geomagnetic records accumulated since about 1850--over a centry now. I gave to this project the name World Magnetic Archive (WMA), and proposed also as a secondary part of it the reproduction on microfilm of the magnetograms from which the hourly records were taken.

Figure 4. Extract from the IAGA News 1969 devoted to archiving the geomagnetic observations and dissemination of the geomagnetic data.

tized. Considering another terrestrial planet, we would like to mention Mariner 10 in 1974 and 1975, the first spacecraft to visit Mercury. The MESSENGER spacecraft has mapped the Hermean magnetic field, and the two spacecraft of the BepiColombo mission will orbit Mercury in the near future. The magnetic fields of giant planets have been surveyed by the Cassini and Juno missions, among others.

The discovery of the solar wind has been an outstanding achievement in heliophysics and space physics (for this early history, the reader is referred to Obridko and Vaisberg, 2017). The first satellites designed to observe the interplanetary medium were NASA Pioneers 5, 6, 7, 8 and 9, launched between 1960 and 1968. In the 1970s, two HELIOS spacecraft provided valuable new data on the solar wind and corona. One of the most important solar missions to date has been the Solar and Heliospheric Observatory (SOHO), launched in 1995. The Solar Dynamics Observatory (SDO) spacecraft, launched in 2010, has provided a closer look at the Sun, the source of all space weather effects. The solar wind and the heliosphere are a natural plasma laboratory energized by constant free energy input from the Sun. Division IV as well as the newly formed Interdivisional Commission on Space Weather are involved in these research fields.

3.3 Geodynamo, paleomagentism and archeomagnetism, magnetotellurics

Larmor (1919) proposed that the magnetic field of the Earth (and Sun) could be maintained by a self-excited dynamo. This idea became generally accepted some 20 years later, assuming that magnetohydrodynamic dynamo theory in a liquid core is responsible for a self-sustaining dynamo. However, the main development was facilitated by computational and experimental facilities during the last decades of the 20th century, with the first demonstration of a successful ("Earth-like") numerical dynamo by Glatzmaier and Roberts (1995a, b).

This development, along with natural curiosity in the history of the geomagnetic field, represents the main justification for paleomagnetism and archeomagnetism, research fields which aim to get information about the intensity and direction of the geomagnetic field over the whole of geological history. Moreover, paleomagnetism helps in understanding processes in the geological history of the Earth, such as reversals of the geomagnetic field, sea-floor spreading, and plate tectonics (introduced already by Wegener in 1915). Actually, the first clear geophysical evidence of continental drift was provided by Runcorn (1956a, b) and Irving (1956), who constructed apparent polar wander paths for Europe and North America.

In the late 50s and early 60s of the last century, magnetic stripes were recorded by a magnetometer towed behind a vessel above the sea floor (Mason and Raff, 1961; Raff and Mason, 1961). A Canadian geophysicist, Lawrence Morley, was one of the first to suggest that the magnetic anomalies could be a kind of tape recorder of the symmetric spreading of the ocean floor through time. In early 1963, Morley submitted his hypothesis to Nature and then to the Journal of Geophysical Research. Both journals rejected his idea as too speculative. In June of that year, he presented his idea to the Royal Society of Canada (Morley, 1967; Emiliani, 2005). In September 1963, Nature published essentially the same hypothesis by British scientists Vine and Matthews (1963). It was subsequently widely accepted, and they received credit for the idea. In time, Morley's contribution was also recognized, and the concept is now known as the Vine–Matthews–Morley hypothesis. The magnetic stripe observations remained a mystery until a generally accepted explanation was published by Vine (1966), interpreting them as records of changing polarity of geomagnetic fields during ocean-floor spreading.

Mercanton (1926) postulated that reversals of magnetic inclination found in the Northern Hemisphere would be found also in the other hemisphere, thus providing evidence that magnetic poles have undergone enormous displacements. He asked IUGG/IAGA to extend its observational (paleomagnetic) base and pointed to the need for centralized sample archiving and unification of methods to study magnetic properties of rocks. At present, many such standardized methods are used in rock, paleo and archeo magnetism, e.g. determination of paleointensity or paleopole positions and characterization of magnetic anisotropy. The IAGA paleomagnetic community realized that the increasing number of laboratories, methods, instruments, and, above all, data requires systematic archiving and easy access. Currently, several regional and global databases exist and are updated, and the Division I role in these activities should be noted.

Magnetotellurics is a method based on the natural variations of the Earth's magnetic and electric fields on the surface used to infer the subsurface electrical conductivity. The penetration depth varies from a few hundreds of metres to 10 km or deeper. The method was developed independently in Japan in the 1940s, and in France (Cagniard, 1953) and in the USSR during the early 1950s, and is currently widely used in exploration surveys, deep crustal and mantle studies and earthquake precursor prediction research. The important role of these activities resulted in conversion of a former working group to Division VI.

4 Aeronomy

The term *aeronomy* was introduced by Chapman (1946) in a letter to Nature, suggesting that aeronomy should replace meteorology as the "meteor is now irrelevant and misleading". This proposal was apparently not received with much support. Thus, in his short note Chapman (1953) wrote that "If, despite its obvious convenience of brevity in itself and its derivatives, it does not commend itself to aeronomers, I think there is a case for modifying my proposal so that instead of the word being used to signify the study of the atmosphere in general, it should be adopted with the restricted sense of the science of the upper atmosphere, for which there is no convenient short word." In 1960, Champan noted that "Aeronomy is the science of the upper region of the atmosphere, where dissociation and ionization are important". Today it includes the science of the corresponding regions of the atmospheres and ionospheres of the Earth and other planets.

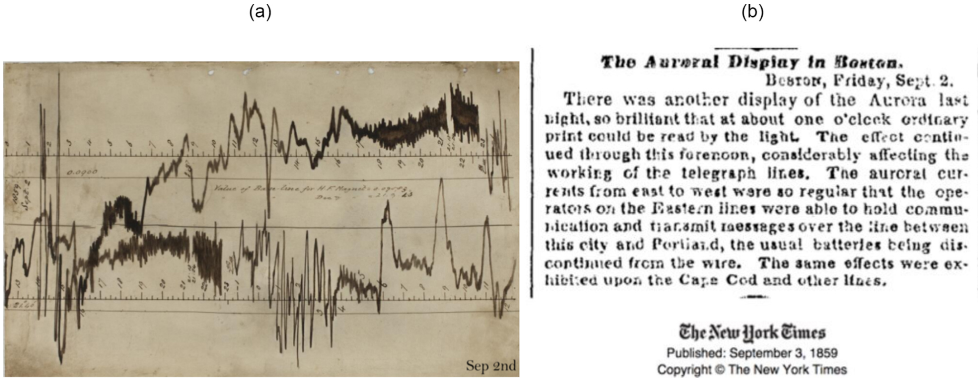
Research in aeronomy requires, in addition to ground-based observations, access to observations obtained from rockets or satellites. IAGA has largely contributed in collaborations with other associations and in coordinating some of the worldwide activities in aeronomy during the international years starting with IGY. In those early days, IAGA Commission VIII was concerned with the "Upper atmospheric structure dealing with electrodynamics, involving aeronomic processes on neutral and ionized particles". Several continuous efforts were aimed at encouraging research in new areas. For instance, in a joint resolution issued in 1963, IAGA-IAMAP recommended global studies of lunar-induced geophysical variations, including those arising from lunar atmospheric tides, which had not been studied as much as solar tides. During the IQSY (1964–1965). Four of the 10 IQSY reporters for various disciplines (drawn from different unions, associations, and committees of ICSU) were from IAGA. In addition to the reporter for geomagnetism, the other three IQSY reporters from IAGA were for aurora, airglow, and aeronomy (Beynon, 1964). The URSI/IAGA Joint Working Group on "Structure and Dynamics of the Thermosphere, Ionosphere, and Exosphere" was established in 1974. At its 6th Scientific Assembly in 1989, IAGA decided to designate the period from September 1991 to March 1993 as the International Equatorial Electrojet Year (IEEY). An IAGA/URSI joint working group on "VLF/ELF Remote Sensing of the ionosphere and magnetosphere" (VERSIM) was set up in 1975 (originally with a different name), and this group continues to be very active, holding a biennial international workshop. In recent years, IAGA has collaborated with the International Commission on Middle Atmosphere (ICMA) of IAMAS to hold a series of workshops on "Long term changes and trends in the Atmosphere", a topic of current interest in view of the anthropogenic contribution to changes in Earth's atmosphere.

IAGA scientific assemblies have provided a platform for reporting the progress achieved in recent years in the fields of mesosphere–lower thermosphere dynamics and chemistry; vertical coupling by upward-propagating waves; ionospheric electrodynamics and structuring; thermosphere–ionosphere coupling, dynamics, and trends; and ionosphere–thermosphere disturbances and modelling (Abdu et al., 2011). All these advanced studies dramatically contributed to the understanding of the variability of Earth's ionosphere, an important component of space weather, and represent the core of activities of Division II.

5 Magnetosphere, magnetic storms, and space weather

The Earth's magnetosphere is the region of space surrounding our planet where its own magnetic field, rather than of the solar wind, is dominant. Although the idea of the Earth's magnetosphere can be found already in the work of Gilbert (1600), the term "magnetosphere" was first proposed by Gold (1959). The magnetosphere is controlled by the interaction of the solar wind with the Earth's magnetic field, with short-term disturbances known as geomagnetic storms. These have significant technological and societal impacts on the ground as well as on orbiting objects.

The great solar storm of September 1859 (Fig. 5), generally referred to as the Carrington Event (Carrington, 1860; Hodgson, 1860; Stewart, 1861), was related to large sunspot groups during solar cycle 10. In retrospect, we know that this solar flare (the first ever reported) was associated with a major coronal mass ejection (CME) that travelled directly



The Auroral Display in Boston.

BOSTON, Friday, Sept. 2.

There was another display of the Aurora last night, so brilliant that at about one o'clock ordinary print could be read by the light. The effect continued through this forenoon, considerably affecting the working of the telegraph lines. The auroral currents from east to west were so regular that the operators on the Eastern lines were able to hold communication and transmit messages over the line between this city and Portland, the usual batteries being discontinued from the wire. The same effects were exhibited upon the Cape Cod and other lines.

The New York Times
Published: September 3, 1859
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Figure 5. A magnetogram of one magnetic storm of 1859, known as the Carrington Event, the same event recorded at Greenwich Observatory in London **(a)**; New York Times report on the same event **(b)**.

to Earth in 17.6 h, to cause the great storm (Bartels, 1937). Aurorae were seen around the world, those in the Northern Hemisphere as far south as the Caribbean; those over the Rocky Mountains were so bright that their glow awoke gold miners, who began preparing breakfast because they thought it was morning. People who happened to be awake in the northeastern US could read a newspaper by the aurora's light. Telegraph systems all over Europe and North America failed, in some cases giving telegraph operators electric shocks. Telegraph pylons threw sparks. Some telegraph systems continued to send and receive messages despite having been disconnected from their power supplies.

Studies have shown that a solar storm of this magnitude occurring today would likely cause widespread problems for modern civilization, mainly because of its impact on the power grid through geomagnetically induced currents or on the performance of satellite-based communication and navigation systems such as GNSS. There is an estimated 12 % chance of a similar event occurring between 2012 and 2022 (Riley, 2012). For example, it is assumed that the major solar eruptive event of July 2012 was at least as strong as that in September 1859 and it was fortunate it did not occur a week earlier when the CME would have been directed to Earth (Baker et al., 2013, 2014). Divisions II, III and IV are deeply involved in space weather research. Moreover, IAGA established an Interdivisional Commission on Space Weather, which encourages research into space weather, geomagnetism and aeronomy, and on space weather impacts on society.

6 IAGA products

IAGA also provides several products, tools, and standards, which are developed by its Divisions and Working Groups. These efforts of all Divisions and Interdivisional Commissions are remarkable, and here we summarize a few of them.

6.1 Models

IGRF. The International Geomagnetic Reference Field (IGRF) is a series of mathematical models of Earth's core magnetic field and its secular variation. The models are used to calculate the large-scale, internal, part of Earth's magnetic field at times between 1900 and the present, at locations on or above the Earth's surface. IGRF has been maintained since 1968 by a working group of volunteer scientists from several international institutions, which was initiated by discussions started in the early 1960s. The IGRF models are used in e.g. studies of space weather, investigations of local magnetic anomalies, and also by commercial organizations and private individuals who often use the geomagnetic field as a source of orientation information. Temporal variations of the internal part of the geomagnetic field, which are on timescales of months to decades, require revisions of the IGRF to remain up to date and as accurate as possible. The first-generation IGRF (IGRF-1) for the period 1955–1975 was published by Zmuda (1971). At present, IGRF-12 (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html, last access: 15 October 2018) extends and updates previous versions (Finlay et al., 2010) and provides a new Definitive Geomagnetic Reference Field model for epoch 2010. Moreover, it proposes a provisional reference field model for epoch 2015 and a predictive part for epochs ranging from 2015 to 2020 (Thébault et al., 2015a, b).

WDMAM. Marine and airborne magnetic anomaly data have been collected for more than half a century, providing global coverage of the Earth. Due to the changing main field from the Earth's core, and due to differences in quality and coverage, combining these data into a consistent global magnetic grid is challenging.

The World Digital Magnetic Anomaly Map (WDMAM) project is an international effort, coordinated by IAGA and started at the end of 1970s, with the goal of integrating all available near-surface and satellite magnetic anomaly data. In 2003, a task force was created with the aim of compiling the WDMAM, combining aeromagnetic and marine data worldwide on a global, 5 km cell size, grid. The first version of the WDMAM was released in 2007 (Korhonen et al., 2007; Hemant et al., 2007) and published by the CGMW. Maus et al. (2009) and Maus (2010) continued collecting data and proposed their own map and associated magnetic field model covering spherical harmonic degrees from 16 to 720. The main limitation of this original grid was the way the oceanic data gaps were filled. Thus, a second version of the map was produced (Lesur et al., 2016). This version was approved by IAGA during the 26th IUGG General Assembly in Prague, Czech Republic, in 2015 and publicly released (http://www.wdmam.org, last access: 15 October 2018).

6.2 Geomagnetic indices

In 1906, the Central Bureau of Terrestrial Magnetism for the calculation of the "International Magnetic Character" was founded and hosted by the Koninklijk Nederlands Meteorologish Instituut (De Bilt, the Netherlands) until 1987. During the IUGG meeting in Vancouver, 1987, it was decided to move the International Service of Geomagnetic Indices (ISGI) to France, and in 2015 the ISGI headquarters moved to Ecole et Observatoire des Sciences de la Terre (EOST) in Strasbourg (http://isgi.unistra.fr/index.php, last access: 15 October 2018).

A geomagnetic index is a generalized measure of the ground magnetic variations observed within a certain longitudinal range. Each index reproduces a specific electric current flowing in the near-Earth space. The evolution of geomagnetic index activity management speaks to the importance of IAGA as a reference body for policy in the matter of indices. ISGI and the ISGI collaborating institutes have the responsibility to ensure the homogeneity of the data series and the quality data stamping in close cooperation with observatories and research activities. IAGA officially recognizes several magnetic indices, aimed at describing the geomagnetic activity or some of its components: aa, am, Kp, Dst, AE, and PC. IAGA also endorses lists of remarkable geomagnetic events such as storm sudden commencement (SSC), solar flare effects (SFEs), and international quiet (Q-days) and most disturbed days (D-days). Criteria for IAGA endorsement of indices became effective in 2009. For more information on computation and use of geomagnetic indices, see e.g. http://isgi.unistra.fr/about_indices.php (last access: 15 October 2018) or https://www.ngdc.noaa.gov/IAGA/vdat/ (last access: 15 October 2018).

7 IAGA in 5, 10, 100 years from now

IAGA is and will remain a strong association in its field of activity. During the upcoming years, IAGA will play a major role in our research to understand our magnetic planet and other planetary bodies. From continuous observations to sophisticated models, the scientists of IAGA will bring new inputs in a better knowledge of how the geodynamo works, of the magnetic lithosphere, and the Earth–Sun environment and interactions. The magnetism of our solar system will continue to be observed and interpreted: the planetary magnetism will bring, undoubtedly, more surprises.

Despite all the technological progress, it is obvious that ground-based observations remain crucial for reliable recording of the geomagnetic field and its variations. Although we do have comparatively good coverage by land observatories, oceans still represent a large blank spot on the observatory map. Therefore, IAGA strongly encourages deployment of seafloor magnetic observatories, which would reduce the gap in the Earth's observation coverage and would lead to significant improvements of the geomagnetic field models and yield associated technical and societal benefits. Seafloor geomagnetic observatory programmes already exist and their installation and operation represent one of the major challenges in geomagnetism. On the other side of future IAGA activities, we can note that new satellites and planet rovers will represent major steps towards a better understanding of planetary fields and space-related events. The ESA Swarm trio of satellites, complemented by Canada's Cassiope satellite, all launched in 2013, have already brought new data needed for our understanding of how the Earth's magnetic field is generated and how it protects us from the intervention of harmful charged particles from outer space. New ideas for a constellation of NanoMagSat are under development (Hulot et al., 2018). Progress in geodynamo, paleomagnetism or magnetotellurics will be mostly determined by experimental, technological and computational facilities. These will also shape the future progress of new discipline – data assimilation, which combines the observations, models, and governing physical laws in order to identify the initial conditions and/or to obtain reliable forecasts of the system evolution. It is very likely that a number of minor steps in these fields will result in achieving more reliable and more complex knowledge of the processes in the interior and on the surface of the Earth and other planetary bodies, including their history.

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IASPEI: its origins and the promotion of global seismology

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Abstract. International cooperation in seismology emerged rapidly at the beginning of the 20th century following the successful recording of earthquakes at great distances. The International Seismological Association (ISA) founded in 1904 was dissolved in 1922 and evolved into the Seismology Section of the International Union of Geodesy and Geophysics (IUGG), ultimately becoming the International Association of Seismology and Physics of the Earth's Interior (IASPEI) to recognize the important role of the structure and physical properties of the Earth. Through the last hundred years, the commissions and working groups of the association have played a major role in setting international standards in such areas as the naming of seismic phases, data exchanges, travel-time tables, magnitude scales, and reference Earth models. The activities of IASPEI continue to have a focus on the societal impacts of earthquakes and tsunamis, with four regional commissions playing a major role in promoting high standards of seismological education, outreach, and international scientific cooperation.

1 Introduction

The International Association of Seismology and Physics of the Earth's Interior (IASPEI) has origins in the last decades of the 19th Century, when seismology was emerging as an important discipline within the newly established scientific field of geophysics. At that time seismology rapidly evolved from a predominantly phenomenological topic to a more theory-based science with expanding instrumental observations validating predictions from elasticity. During this period, scientists in many countries began to systematically collect data for macroseismically observed earthquakes, with approximate locations of these events being only known on the basis of such data. In some countries, scientists and/or their governments established special committees or commissions to do such work. To the best of our knowledge, the Erdbebenkommission der Schweizerisch Naturforschenden Gesellschaft (Earthquake Commission of the Swiss Society for Natural Scientists) was the first such commission, founded in Switzerland in 1878, followed in 1879 by the Regio Uffizio Centrale di Meteorologia e Geodinamica (Royal Central Office for Meteorology and Geodynamics) in Italy. In Japan, the first nationwide working service for earthquake observations was established after the foundation of the initial worldwide Seismological Society in 1880. During the following years, earthquake commissions, committees or equivalent institutions were founded in many European countries (see, for example, Sieberg, 1904). In parallel, new types of seismological instruments were developed and installed in Italy, Japan, and Germany, and a more or less continuous registration of sparse global ground motions became possible from the 1880s on. Detailed descriptions of the history of development of ground motion recording instrumentation in the early days of seismology can be found in Ehlert (1898), Berlage Jr. (1930), Dewey and Byerly (1969), and Ferrari (1990, 1992).

Because of improved instrumentation after the late 1890s, seismic observations were increasingly published with physically measured parameters, i.e., measured onset times, dominant periods, and amplitudes of seismic waves. However, seismologists were still learning how to interpret their observations, mostly empirically. By the early 1900s, first-order features of the seismic records were being understood as the recording instruments produced seismograms with enough resolution in time and dynamic range to distinguish between onsets of all three theoretically expected wave types (i.e., longitudinal or primary waves (P waves) and shear or secondary waves (S waves) traveling through the interior of the Earth as body waves, as well as surface or long period waves (L waves) traveling along the Earth's surface). The first versions of the current nomenclature for seismic phases were developed (von dem Borne, 1904; Bormann et al., 2013). Then, phase-specific observations began to be collected and published in seismic bulletins. A detailed description of the different types of seismic bulletins and their development until 1920 can be found in Schweitzer and Lee (2003).

One key discovery of the early days of seismology was the first observation of a teleseismic signal from an earthquake at about 80° epicentral distance by Ernst von Rebeur-Paschwitz (1861–1895, Fig. 1). This astronomer had installed two identical horizontal pendula at Potsdam and Wilhelmshaven in Germany, separated by a distance of about 240 km. His intent was to measure ground movements caused by the gravitational effect of celestial bodies (Moon, Sun, comets, etc.), which he achieved: Rebeur-Paschwitz confirmed for the first time the theoretically expected movements of the solid Earth due to the tides (von Rebeur-Paschwitz, 1892). On 17 April 1889, he recorded strong signals with both instruments (Fig. 2) and worked to exclude all types of astronomical and non-celestial explanations. In a letter published in *Nature*, he associated his observations with a large earthquake felt on the Izu Peninsula (Izu Hantō), Japan, and located west of Izu Ōshima (34.75° N, 139.33° E) by the Central Meteorological Observatory in Tokyo (von Rebeur-Paschwitz, 1889). More about von Rebeur-Paschwitz and his contributions to seismology can be found in Davison (1978) or Schweitzer (2003). With this observation, seismology changed from a local/regional focus to a global science. Von Rebeur-Paschwitz continued to search for teleseismic signals, perceiving the advantages of using seismic waves as a tool to investigate the Earth's interior, and came in contact with the British seismologists working at that time in Japan. In his last publication (von Rebeur-Paschwitz, 1895) he argued for establishing a global network of seismometer stations with globally synchronized timing (Greenwich Mean Time) and an internationally centralized bureau to collect global seismological observations.

2 1904–1922: the International Seismological Association (ISA) as IASPEI ancestor

Georg C. K. Gerland (1833–1919) presented von Rebeur-Paschwitz's proposal at the Sixth International Geographical Congress, London, in 1895 and promoted it further after von Rebeur-Paschwitz's early death. The ideas were embraced by many colleagues and in 1901 Gerland welcomed colleagues from Austria–Hungary, Belgium, Denmark, Germany, Italy, Japan, Russia, and Switzerland at the First International Seismological Conference in Strasbourg, at that time a town in Germany, to discuss seismology and how to organize international seismological cooperation. In addition, colleagues from France, Great Britain, Greece, New Zealand, Norway, Portugal (Azores), Sweden, and the Netherlands sent their greetings and excuses for not being able to participate in the conference (see Rudolph, 1902). The not always politically easy discussions (e.g., dichotomy between a governmental and scientific association) were continued during the Second International Seismological Conference in 1903 (also in Strasbourg) with delegates and participants from 20 states, and this resulted in the drafted convention for an international organization for which states could become paying members; the International Seismological Association (ISA) (see Rudolph, 1904). The ISA convention entered into force on 1 April 1904 with 18 states as founding members and was planned to continue for a period of 12 years (until 31 March 1916). More details about the discussions and politics involved in the ISA foundation can be found in Rudolph (1902, 1904), Hodgson (1967), Rothé (1981), and Schweitzer (2003, 2007). As proposed by von Rebeur-Paschwitz, an important part of ISA became the newly founded Central Bureau located with its Director in Strasbourg. Years later, in 1927, Davison dedicated his monograph *The Founders of Seismology* to von Rebeur-

Figure 1. Ernst von Rebeur-Paschwitz (1861–1895). Courtesy of Universitätsarchiv Tübingen (UAT 209/108, Bl 10).

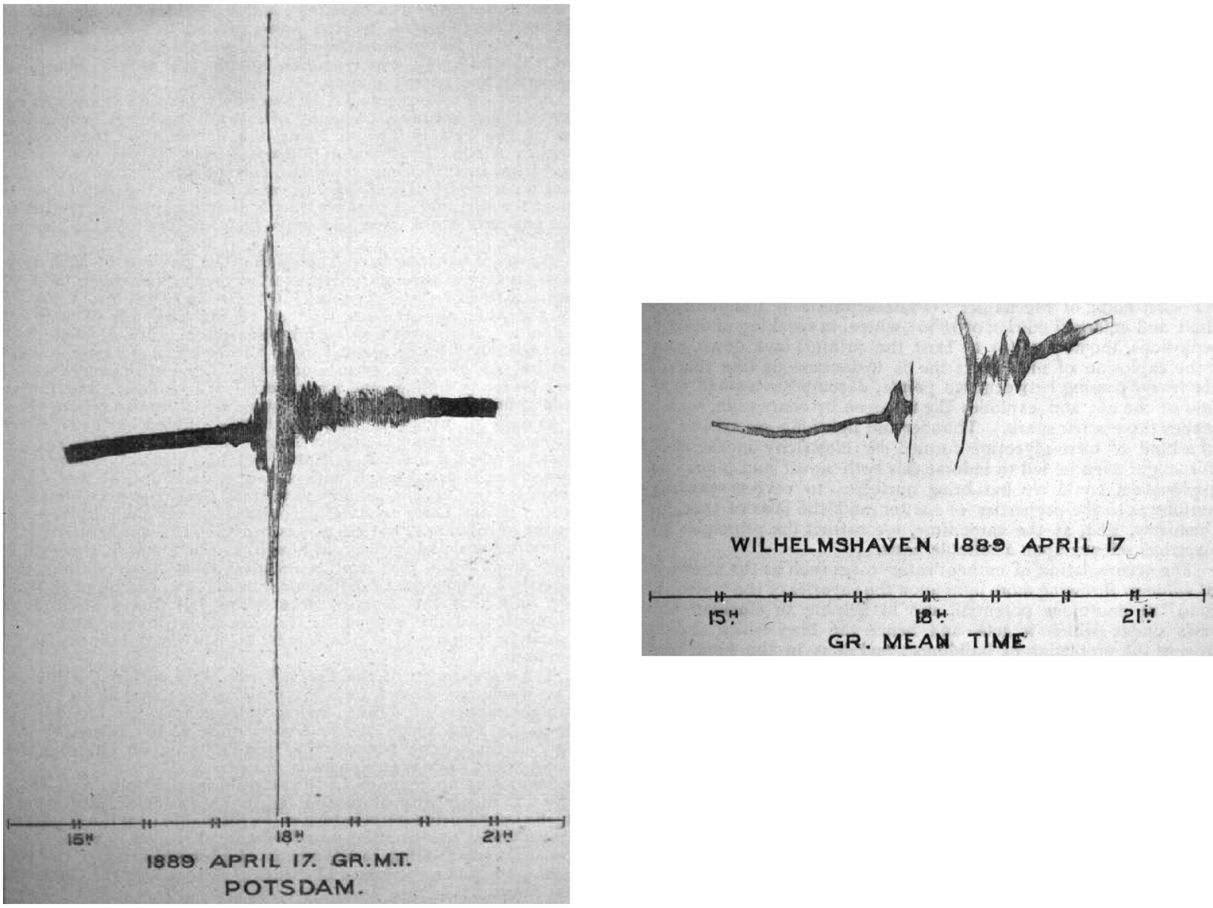

Figure 2. The 17 April 1889 seismogram records in Potsdam and Wilhelmshaven, from von Rebeur-Paschwitz (1889).

Paschwitz along with John Milne (1850–1913) and Fusakichi Omori (1868–1923). Following Rothé (1981), Gerland can be called the founder of IASPEI, but the fundamental ideas stem from von Rebeur-Paschwitz.

The main tasks of the Central Bureau were the collection of observed parametric data from all globally distributed seismic stations, associating these observations to seismic events, locating these events, and publishing a global bulletin. During the following years, the Central Bureau

– published global and regional earthquake catalogues and bulletins for macroseismically and instrumentally observed earthquakes for the years 1903–1908 (for details see Schweitzer and Lee, 2003);

– published monographs and articles about different aspects of seismology, as macroseismic studies, instrumentation, event location techniques, and special publications on important earthquakes;

– distributed newsletters (*Mitteilungen des Zentralbureaus der Internationalen Seismologischen Assoziation*) during World War I with similar contents;

– installed and supported two international seismic stations, one on Iceland and one in Lebanon;

– edited the globally distributed German issue of Prince Boris Galitzin's classical textbook *Vorlesungen über Seismometrie* (Galitzin, 1914);

– and organized an evaluation competition on seismographs.

An ISA publication list can be found in the archive section of the IASPEI website (http://iaspei.org/documents/publications, last access: 22 January 2019).

A permanent commission was formed as a steering committee with an ISA President and a Secretary General during the Berlin conference (1905), and it met again in Rome (1906), The Hague (1907), Zermatt (1910), Manchester (1911), and Strasbourg (1922). General assemblies of ISA were held jointly with the meetings of the permanent commission in The Hague (Fig. 3), Manchester, and Strasbourg. The ISA convention had expired during World War I in 1916 and was not extended. Many seismic stations worldwide stopped operating (Schweitzer and Lee, 2003) because the staff had to participate in the war, and the international cooperation in seismology largely broke down. After World War I, international scientific cooperation was reorganized in a framework devised by the winning powers, with the International Union of Geodesy and Geophysics (IUGG) being founded in 1919, at the General Assembly of the International Research Council. In April 1922, the International Seismological Association was officially dissolved by the Strasbourg General Assembly (de Kövesligethy, 1922; Rothé, 1981). From this meeting, the delegates directly traveled to the First IUGG General Assembly in Rome, in May 1922, where the Seismology Section was formed as part of the IUGG.

3 1922: the International Association of Seismology and Physics of the Earth's Interior (IASPEI) as part of IUGG

The Seismology Section of the IUGG continued working in the spirit of ISA and changed its name to the International Association of Seismology at the Fourth IUGG General Assembly, in Stockholm, in 1930. Later, during the Ninth IUGG General Assembly in Brussels, in 1951, the association again changed its name to the International Association of Seismology and Physics of the Earth's Interior (IASPEI). For detailed accounts of the organizational history of IASPEI, see Hodgson (1967), Rothé (1981), and Adams (2002).

For about 50 years, the official Bureau of the Association was located in the now French town of Strasbourg, as the Central Bureau of ISA had been before, where the Secretaries General Edmond Rothé (1873–1942) and his son Jean-Pierre Rothé (1906–1991) edited and published the *Publications du Bureau Central Séismologique International* as *Série A, Travaux Scientifiques* (1924–1968), and as *Série B, Monographies* (1924–1937), as well as the Proceedings and Reports from the assemblies (*Comptes Rendus*). In addition, the Bureau in Strasbourg also continued to publish preliminary seismic bulletins and earthquake locations. However, in 1922, the compilation of the final global seismic bulletin was ceded by the association to Herbert H. Turner (1861–1930) in Oxford, who had already published the *Bulletin of the British Association of the Advancement of Science, Seismology Committee* for the years 1913–1917, which was a continuation of John Milne's *Shide Circulars* (1899–1912) (for more details see Schweitzer and Lee, 2003). The IASPEI bulletin for the years 1918–1963 was edited and published as the *International Seismological Summary* (ISS) in the UK (Stoneley, 1970). However, during and after World War II, a period of decline for international cooperation in seismology occurred (as during and after World War I): again, many seismic stations had to interrupt their operation and seismic monitoring became quite fragmentary.

As successor to the ISS, the International Seismological Centre (ISC) was set up with the help of UNESCO in 1964 to produce the global *Bulletin of the International Seismological Centre*. The ISC is no longer a formal part of IASPEI, but it operates under the umbrella of IASPEI and has always sustained very close scientific links with IASPEI, as demonstrated by the ISC Governing Council having its meetings during the biannual IASPEI assemblies. Summaries of the ISC activities can be found in the yearly reports of the ISC Director (http://www.isc.ac.uk/docs/dirreport/, last access: 22 January 2019).

4 Some scientific achievements by IASPEI during the last 100 years

After recognizing the need for international cooperation in seismology, many scientific achievements have been connected with IASPEI and its forerunners. Of course, most scientific discoveries are related to individual scientists, but the association provided seismologists and geophysicists a forum to meet regularly and exchange ideas, and to present and discuss their findings. However, some of these achievements are directly connected with the work within the association or were later adopted by the association and became thereby international standards.

During the last nine decades, the association had different commissions and working groups which played an unsurpassed role in unifying seismological observations; e.g., naming seismic phases, defining measurement procedures, testing seismic instruments, defining standard formats for data exchange, collecting and distributing seismological software, improving the network of seismic stations, producing reference Earth models, and publishing scientific results.

During the first decades of the last century, the principal layered structure of the Earth with a crust, mantle, and core had been revealed by different seismologists. However, Turner's discovery of seismic events with hypocenters located deep in the upper mantle was only possible with the help of globally distributed seismic stations and the collection of seismic observations by the ISS and can be counted as a direct result of association activities. Over subsequent decades, several contributions during association assemblies and in their publications by different authors were related to the problem of understanding deep focus events.

The data collection of the association during the late 1920s and early 1930s provided a source for Inge Lehmann's (1888–1993) early travel-time table studies. The highlight of these studies, partly supported by a grant of the association, was the publication of an article in the *Travaux Scientifiques* with one of the shortest titles ever: P'. In this paper, Inge Lehmann proposed the existence of an inner core of the Earth (Lehmann, 1936). In the same year, during the Sixth IUGG General Assembly in Edinburgh, Inge Lehmann became the first female member of the IASPEI Executive Committee.

In general, seismic travel-time tables and seismic-phase identification have long been a major topic of interest for IASPEI. IASPEI published several travel-time tables for dif-

Figure 3. Participants of the First General Assembly of the International Seismological Association in The Hague, the Netherlands, 21–25 September 1907. Courtesy of the German GeoForschungsZentrum (GFZ, German Research Centre for Geosciences), Potsdam.

ferent seismic phases from different authors and founded, during the Fifth IUGG General Assembly in Lisbon (1933), a commission for the publication of new seismic travel-time tables. Mostly derived from the data collection at the ISS, the result of this international effort was the Jeffreys–Bullen tables published in its final version in 1940 (Jeffreys and Bullen, 1940). These seismic travel-time tables became the primary basis for seismic event locations worldwide and were used at the ISS/ISC until 2008.

The relationship between ISS/ISC and IASPEI can be described as symbiotic. Based on the data collections in the seismic bulletins, scientists investigated the internal structure of the Earth and ISS/ISC staff were and are active in the IASPEI Commission of Seismological Observation and Interpretation and in promoting the standardization of routine analysis at the seismological observatories to produce better seismic bulletins such as the *International Seismic Bulletin Format* (ISF), *The IASPEI Standard Seismic Phase List*, and *The new IASPEI standards for determining magnitudes from digital data and their relation to classical magnitudes*, which are all part of the *IASPEI New Manual of the Seismological Observatory Practice* (NMSOP-2) (Bormann, 2012). This manual is the latest issue of a series of IASPEI-supported publications, which started in the 1950s as a tool to improve and standardize seismological analysis practice and knowledge worldwide.

Without this cooperation, the great achievements in understanding the dynamics, structure, and history of the solid Earth would not have been possible: all modern global standard Earth models and numerous regional models are based on data collected at the ISC and were often initiated by IASPEI working groups such as the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981) and the seismic travel-time models IASPEI91 (Kennett and Engdahl, 1991), SP6 (Morelli and Dziewonski, 1993) and AK135 (Kennett et al., 1995). Since 2008, AK135 has been the standard travel-time table for locating seismic events at the ISC.

The scientific interests of the association were not only focused on seismological topics, but on all questions related to structure and physical properties within the Earth. Consequently, during the Ninth IUGG General Assembly in Brussels (1951), the association changed its name to the current IASPEI and added to its fields of interest tectonophysics, geothermy, radioactivity, petrophysics, geodynamics, elasticity, and plasticity. A new Commission of Physics of the Earth's Interior (Commission de Physique de l'Intérieur de la Terre, today the IASPEI Commission on Earth Structure and Geodynamics) was formed and later IASPEI became involved in many international projects with designated working groups and sessions during general and scientific assemblies such as the international Upper Mantle Project (1964–1970), the Geodynamics Project (1970–1979), and the still ongoing International Lithosphere Program (ILP) (since 1980).

The now $\sim$ 50-year-old modern understanding of plate tectonics with its principal plate boundary system of subduction zones, transform faults, and spreading ridges would not have been possible without high-quality earthquake locations, stress distributions along plate boundaries derived from seismicity studies, and detailed understanding of earthquake source mechanisms. All these questions and concepts were discussed extensively during many IASPEI assemblies and these topics benefited directly from the international cooperation organized by IASPEI (e.g., in the IASPEI Commission on Tectonophysics and Crustal Structure). The same is true for most of the modern 3D tomographic models of seismic velocities in the Earth's mantle, which are based on globally collected travel-time and waveform observations from many international networks of seismometers. These models provide the foundations for modeling convection of material and thermal evolution within the Earth.

5 The societal impact of IASPEI-promoted research

All the above-mentioned research topics have as a common goal a better understanding of structure and dynamics of our planet, in its past, present, and future. The most dramatic evidence that the solid Earth is dynamic and in permanent change is earthquakes, volcanic eruptions, and tsunamis. These ground movements and dynamic processes are of basic scientific interest, but they also can have dramatic consequences for life on Earth. Earthquakes have caused millions of casualties during the last 100 years and IASPEI has a major responsibility to help mitigate the social impact and risk of earthquakes, tsunamis, and volcanoes by contributing its globally collected seismological knowledge.

To understand the seismic hazard of specific regions, seismologists in IASPEI and its regional commissions are working on the compilation of earthquake catalogues, which must be as complete as possible, with highly accurate earthquake locations and magnitude estimates. For such studies the best background material is the instrumentally observed seismic event catalogues, compiled in the name or under the umbrella of IASPEI during the last ~ 100 years. Since this is a relatively short time period for understanding long-term hazard, special working groups within IASPEI are working on the extension of earthquake catalogues to the past by studying historical sources and/or geological data. Other input to seismic hazard comes from studies of seismotectonics and the current stress field in the Earth's crust based on accurate earthquake source parameters. In particular the physical processes in seismic sources are studied in the IASPEI Commission on Earthquake Source Mechanics and the IASPEI Commission on Earthquake Generation Process – Physics, Modelling, and Monitoring for Forecast.

In contrast to other natural hazards, earthquakes and tsunamis can cause damage and loss of lives at large distances from the actual source due to wave propagation. Seismic (and tsunami) wave propagation and their effects have always been topics of IASPEI commissions or working groups. It is a long tradition in IASPEI to organize special symposia after large earthquake catastrophes or other important seismic events. In the earthquake hazard arena, close cooperation with the earthquake engineering community is essential, where members of the IASPEI Commission on Earthquake Hazard, Risk, and Strong Ground Motion contribute with physical knowledge about seismic wave propagation in soil and buildings and probabilistic assessments of the frequency of certain levels of shaking exposure to help mitigate seismic risk by informed engineering.

The first nuclear weapon test in the desert of New Mexico on 16 July 1945 was recorded by seismic stations (Gutenberg, 1946), introducing a new role for seismological monitoring. The political need for monitoring global nuclear weapon tests helped the international seismological community to develop new seismic instrumentations, to request funding for basic seismological research and cooperation, and to install new seismic stations and networks. IASPEI has always been very active in collecting information to obtain very accurately located seismic events. This information has been very helpful in testing location algorithms, travel-time models, and in calibrating the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), which has been operational during the last two decades. In this way, IASPEI and its members directly contribute to making the Earth a safer place in which to live.

6 IASPEI: regional commissions and the International Federation of Digital Seismograph Networks (FDSN)

In addition to IASPEI's global research activities, it became clear that fostering enhanced regional cooperation and coordination is also needed for both research and hazard applications. As a first step, IASPEI founded in 1951 the Commission pour l'etude des problemes seismologiques Européens (Commission to study European Seismological Problems), which became the nucleus for the well-established European Seismological Commission (ESC). It is worth noting that this commission was for decades one of the few organizations keeping contact and data exchange open between countries in the politically divided Europe after World War II. Later, more regional commissions were founded: in 1996 the Asian Seismological Commission (ASC), in 2011 the African Seismological Commission (AfSC), and in 2013 the Latin American and Caribbean Seismological Commission (LACSC). These regional commissions, with their biannual general assemblies, play today an important role in IASPEI activities.

During its early years, the association played a steady role in testing seismic instruments and promoting the installation of seismic stations. However, during the last few decades many high-quality seismic instruments were developed and today the quality of seismic recordings depends much less on instrumentation and more on local site and installation conditions. In parallel, many new national and international seismic networks have been established and are recording digital seismic signals of high quality, which are often accessible by seismologists in near-real time. To coordinate network planning and to develop standards in digital data quality, exchange, and archiving, the International Federation of Digital

Seismograph Networks (FDSN) was founded in 1986 during the XX ESC General Assembly (in Kiel, Germany) and acquired the status of an IASPEI commission.

7 Future of IASPEI

The future of IASPEI is of course dependent on continuation of international funding and voluntary support of its members, the international seismological community. These factors are closely related to the general social and economic developments in the different member countries and in terms of how much (international) seismological research can contribute to an improved understanding of the dynamic processes in the Earth.

In any case, IASPEI will continue to have a key function in coordinating international cooperation for the seismic monitoring of planet Earth, investigating internal structure, and contributing to the mitigation of earthquake risk. An important aspect of IASPEI activities is that IASPEI assemblies have been organized on different continents and in different countries. This enables different countries and regions to engage with IASPEI and provides opportunities for their researchers to participate in the assemblies and to become acquainted with the global community. The IASPEI regional commissions have a similar function for the different regions. This activity will stay as an important contribution to international scientific cooperation across political and cultural differences.

IASPEI will continue to be the global forum for the definition of all types of standards related to analysis and interpretation of seismic data. After adopting such standards, IASPEI remains committed to its international educational mission to promote and ascertain their application, e.g., by the IASPEI Commission on Education and Outreach.

IASPEI is represented and participates in many IUGG activities (e.g., the Union Commissions Mathematical Geophysics and Study of the Earth's Deep Interior), Inter-Association Commissions (e.g., International Heat Flow Commission, International Ocean Network, Tsunami Commission, Commission on Volcano Seismology), and working groups (e.g., Electromagnetic Studies of Earthquakes and Volcanoes, Seismogeodesy). This results in joint scientific assemblies with other IUGG associations (e.g., in 2003 with IAGA, in 2013 with IAHS and IAPSO, and in 2017 with IAG) and topic-specific symposia during its assemblies. By this effort, IASPEI supports its affiliated members in their interests for exciting, but often very challenging, interdisciplinary research.

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IAVCEI: from small beginnings to a vibrant international association

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Abstract. The International Association for Volcanology and Chemistry of the Earth's Interior (IAVCEI) was formed following the end of World War I at the inaugural general assembly (GA) of the International Research Council in Brussels in 1919, where the International Union of Geodesy and Geophysics (IUGG) was constituted. IAVCEI was then known as the Section for Volcanology (SV) and was one of six scientific disciplines that made up IUGG. The first president of IAVCEI (or SV) was Annibale Riccò (Italy), its first two vice presidents were Alfred Lacroix (France) and Henry Washington (USA), and the first secretary-general (SG) was Alessandro Malladra (Italy). A secretariat office for SV was established in Naples, Italy, following the first IUGG and SV General Assembly in 1922, in Rome, Italy. At that meeting SV established its own scientific journal called *Bulletin volcanologique*, the first edition of which was published in 1924 with Alessandro Malladra as the editor. SV officially became the International Association for Volcanology (IAV) in 1933 at the 5th IUGG General Assembly in Lisbon, Portugal. At the 14th IUGG General Assembly in Zurich, Switzerland, in 1967, IAV was renamed IAVCEI in recognition of the importance of geochemistry and geochronology in understanding volcanic processes. *Bulletin volcanologique* was renamed the *Bulletin of Volcanology* in 1986, at the time that its editorial board was restructured to be more representative of the international community. IAVCEI became a fully democratic association in 1995 with the introduction of individual membership, which entitled members to nominate, be nominated and vote in the election of the IAVCEI Executive Committee. Although the IUGG By-Laws allowed scientists only from the union's member countries to hold various positions within IUGG, in 2015, the IUGG Council removed this restriction, and now a scientist who is a member of IAVCEI from any country can hold any position in IAVCEI, except the position of the president.

1 Introduction

At the end of World War I in 1918, representatives of national academies from the allied nations held meetings in London and Paris to establish the International Research Council (IRC). At the first IRC General Assembly in Brussels in 1919, it was decided that the International Astronomical Union and the International Union of Geodesy and Geophysics would be established (IUGG; Lyons, 1919; Ismail-Zadeh, 2016). IUGG was thus constituted in July 1919 in Brussels, and it brought together several geoscientific disciplines that had existed as independent scientific organisations prior to World War I – geodesy, terrestrial magnetism and electricity, meteorology, physical oceanography, and seismology (Ismail-Zadeh, 2016). Volcanology was also included, even though it does not appear to have had a formal international organisational presence prior to this. These scientific disciplines of IUGG were initially called "Sections" (of IUGG). The International Association for Volcanology and Chemistry of the Earth's Interior (IAVCEI) was therefore initially called the Section of Volcanology (SV) of IUGG when it became constitutionally legitimate in 1919 (Gasparini and Johnson, 1995). The first general assembly of IUGG, and of SV (IAVCEI), was held in Rome, Italy, in 1922.

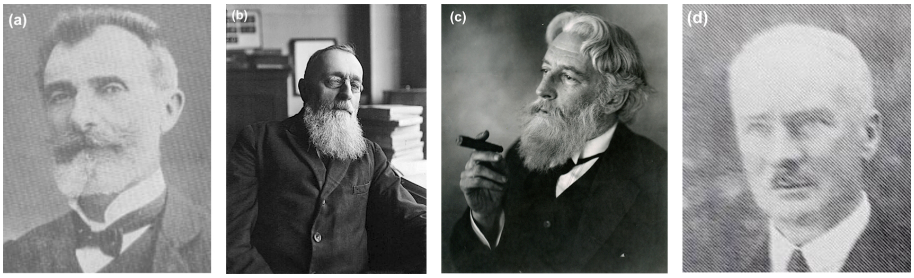

Figure 1. Key personnel responsible for the formation of IAVCEI. **(a)** Annibale Riccò, first president of IAVCEI (source: Osservatorio Astronomico di Palermo website – http://www.astropa.inaf.it/annibale-ricco/, last access: 11 July 2018). **(b)** Alfred Lacroix, the first co-vice president and second president (source: Wikipedia – https://en.wikipedia.org/wiki/Alfred_Lacroix, last access: 11 July 2018). **(c)** Henry S. Washington, first co-vice president (source: Milton, 1991, American Academy of Science). **(d)** Alessandro Malladra, first secretary-general, subsequent president and first editor of *Bulletin volcanologique* (source: http://www.minerbook.it/, last access: 11 July 2018). Parts **(a)**, **(b)** and **(d)** are public domain; part **(c)** permission was granted by US National Academy of Science.

This article traces the evolution of IAVCEI, its governance and activities for its first 100 years as an international learned society or association, from 1919 to 2019.

2 The evolution of IAVCEI

2.1 The movers and shakers behind IAVCEI's formation in 1919

The movers and shakers who are credited with establishing the Section for Volcanology in IUGG in 1919 are Annibale Riccò (Italy), Alfred Lacroix (France), Henry S. Washington (USA) and Alessandro Malladra (Italy; Fig. 1; Gasparini and Johnson, 1995). Annibale Riccò (Fig. 1a) was a celebrated Italian astronomer, with interests in other natural sciences, including seismology. He served as an astronomer at the universities of Modena; Naples, Palermo, and at the time of appointment, Catania (all in Italy). Alfred Lacroix (Fig. 1b) was a French volcanologist at the Museum of Natural History in Paris and was most famous for his account of the 1902 eruption of Mount Pelée, which killed ∼30 000 people in the coastal town of Saint-Pierre, Martinique, and for defining the concept of nuées ardentes ("glowing clouds" or pyroclastic flows). Henry S. Washington (Fig. 1c) was a well-known American petrologist and geochemist at the Carnegie Institute in Washington DC, who was integral to introducing the normative mineralogy composition concept. Alessandro Malladra (Fig. 1d) was an Italian volcanologist from the Vesuvius Observatory in Naples.

At that inaugural general assembly of the International Research Council in Brussels, Belgium, in 1919, where IUGG was formed as a union of six disciplinary sections, Annibale Riccò was elected as the first president of the Section for Volcanology (SV), Alfred Lacroix and Henry Washington were elected vice presidents, and Alessandro Malladra was elected as secretary-general (SG). The process is not clear, but presumably it was by the consensus of the shakers and movers involved in setting up SV. Sadly, Riccò died after only 2 months into his term as president. Lacroix took over the duties of president de facto but was not formally installed as president until the first IUGG General Assembly in Rome, Italy, in 1922, at which Washington was elected vice president and Malladra was confirmed as secretary-general.

2.2 How IAVCEI evolved from 1919 onwards

At the 1922 IUGG General Assembly, SV decided to establish a bureau or office for the section in Naples, Italy, where Malladra was based. In his capacity as secretary-general, Malladra also oversaw the introduction of *Bulletin volcanologique*, the precursor to the *Bulletin of Volcanology* (BV). The title in French accords with French being one of the two official languages of IUGG. The first volume of *BV* was published in 1924, with Alessandro Malladra as the editor. He continued as editor until 1936, in addition to being secretary-general.

IAVCEI's first scientific conference or meeting, where scientists from several countries presented their research, volcanological issues were discussed and reports on significant recent volcanic eruptions were presented, was part of the first IUGG General Assembly held in Rome in 1922. The number of participants was not recorded, but representatives from Belgium, Canada, France, the United Kingdom, Italy, Japan, Norway, Portugal, Spain, Sweden, Switzerland and the USA participated in IAVCEI's first general assembly (Gasparini and Johnson, 1995). At the 4th IUGG General Assembly in Stockholm, Sweden, it was decided to rename the IUGG Sections as Associations (Gasparini and Johnson, 1995), which was implemented at the 5th IUGG General Assembly in Lisbon, Portugal, in 1933 (Ismail-Zadeh, 2016). SV thus became the International Association for Volcanology (IAV) in 1933. At the 14th IUGG General Assembly in Zurich, Switzerland, in 1967, IAV was renamed IAVCEI in recognition of the importance of geochemistry and geochronology in understanding volcanic processes (Gasparini and Johnson, 1995).

Since 1922, IAVCEI has held regular major scientific meetings about every 2 years. The meetings held in conjunction with IUGG General Assemblies were called IAVCEI General Assemblies (GAs; where business and scientific meetings were held); these were held every 2–3 years, and since 1963, they have been held every 4 years, except during World War II (see http://www.iugg.org/assemblies/, last access: 11 July 2018, for a list of dates and locations). In between the GAs, IAVCEI has held its own major conferences, called IAVCEI Scientific Assemblies (SAs), although the one held in 1977 was a joint meeting with the International Association for Seismology and Physics of the Earth's Interior (IASPEI; see Supplement). Attendances have progressively increased from ~ 500 in 1977 at the Durham, UK, SA to >1000 at the 2013 Kagoshima, Japan, SA and 1400 at the 2017 Portland, USA, SA. There was, however, a decrease in numbers immediately after the global financial crisis of 2008. Over the last 20 years, new conferences, initiated by the Commission for Cities and Volcanoes and called "Cities on Volcanoes" (CoV) conferences, have become very popular, attracting over 600 people at recent conferences. These are also held about every 2 years (see Supplement). All conferences are held in different locations and countries, and the venue is based on interested countries competing to host each conference.

3 Governance

3.1 Office bearers and committee

IAVCEI is managed by an elected committee called the IAVCEI Executive Committee. The principal office bearers of IAVCEI have been its presidents and secretaries-general (the latter is also the treasurer). In addition, a committee, variously consisting of one or, more recently, two vice presidents and four other members, provides advice and help in the decision-making process. Together with the president, secretary-general and immediate past president ex officio, they constitute the executive committee of IAVCEI. The current committee is listed on the IAVCEI website (https://www.iavceivolcano.org, last access: 11 July 2018), and the list of past IAVCEI office bearers is summarised in the Supplement. The lengths of committee terms have varied in the past, but since 1963 the terms for all committee members have been 4 years, except for the secretary-general, whose term is 8 years to provide continuity. Committee members can be re-elected after their first 4-year term for only one further 4-year term, but they may nominate for the presidency or secretary-general position thereafter. All committee positions are voluntary, and the IAVCEI community is indebted to those who have given their time to serve as committee members.

3.2 Election of IAVCEI executive committees by IAVCEI members and introduction of individual membership

The IAVCEI Executive Committee is now elected by IAVCEI members in the months before each IAVCEI general assembly, after an open call for nominations from IAVCEI members. The election is conducted by an election oversight committee appointed by the president, and is usually chaired by the past president, two terms earlier. The editor of the *Bulletin of Volcanology* is appointed by the executive committee after an open call for expressions of interest.

Prior to 1995, candidates for the IAVCEI committees were identified following enquiries by the outgoing executive committee about suitable candidates who were representative of the IAVCEI community worldwide. In 1995, under the presidency of Grant Heiken, the IAVCEI Executive Committee introduced personal membership in order to develop a stronger sense of community; to help raise funds for the many meetings and workshops that IAVCEI organised every year, which could not be adequately funded by annual budget allocations from IUGG; and to provide a sounder financial base for publication of the *Bulletin of Volcanology*. As a result, IAVCEI members became eligible to nominate, be nominated and vote for candidates for the IAVCEI Executive Committee. Officially, IUGG did not support individual membership or membership fees in the IUGG associations, and there had been many tense exchanges between IAVCEI and the IUGG executive before and after the 1995 declaration on individual membership. IUGG Statutes stated that the executive committees of the associations could only be voted on by the official national correspondents to each association who could only come from member countries of IUGG with membership dues paid. The problems with this scheme were many, including the disenfranchisement of many volcanologists who were very active in IAVCEI but came from countries that were not financial members of IUGG. This was clearly unfair in an increasingly modern, inclusive and democratic world. So from 1995 onwards, IAVCEI executive committees were elected by all members of IAVCEI irrespective of their countries of residence and contrary to the IUGG Statutes.

Unfortunately, this meant that while IUGG adhered to its statutes, IAVCEI executive committees could be declared illegitimate by IUGG if it chose. To overcome this constitutional impasse, the IAVCEI Executive Committee of 2011–2015 undertook a hard, and again at times tense, campaign to convince IUGG and its other member associations of the merits of allowing associations to introduce individual membership, the charging of membership fees and democratisation of the elections of association executive committees, if they so wished. This involved allowing all registered members, irrespective of country of residence, to be eligible to nominate candidates, to be nominated as a candidate and to participate in the election of the committees. At one stage, IAVCEI considered seceding from IUGG if these basic democratic principles were not agreed to. The proposal was overwhelmingly supported by the IUGG Council at its meeting at the IUGG General Assembly in Prague, given that two other associations also already had a form of personal membership in place, demonstrating that attitudes on personal membership in IUGG were changing. In addition, IAVCEI demonstrated that it was by far the most active association in IUGG in terms of conferences, workshops and short courses, which it could only do using funding generated by personal membership fees.

The only position now on the IAVCEI Executive Committee that must be filled by a representative from an IUGG financial member country is the president. This was a concession to IUGG, since the finances of IUGG, and thus the associations, which all receive an annual monetary allocation from IUGG, are all derived from the subscriptions paid to IUGG by member countries and from the budgets of the national academies of science of those countries. The perceived benefits of being a country member of IUGG is the right to contribute to the formulation of scientific policy at an international level through IUGG and then through the International Council for Science (ICSU), now called the International Science Council (ISC).

From 1995 to 2011, the election of the IAVCEI Executive Committee was conducted by hard-copy ballot papers and snail mail. The elections of the 2011–2015 and 2015–2019 IAVCEI committees were successfully conducted online.

3.3 Statutes

Gasparini and Johnson (1995) note that statutes (or constitution) for the International Association for Volcanology (IAV) were adopted at the general assembly in Helsinki, Finland, in 1960. It is assumed that prior to this IAV Statutes mirrored those of IUGG, although information on this is invited from readers. Following these 1960 statutes, IAV's scientific activities were managed through four sections, namely active volcanoes, volcano-physics, physics and chemistry of magmas, and paleovolcanology, and the presidents of these were members of the IAV Bureau. At the IUGG General Assembly in Zurich in 1967, IAV became IAVCEI, and more flexible working groups on topical research themes were introduced to replace the more rigid sections. There was then a further revision of IAVCEI's statutes at the 1979 IUGG General Assembly, in which "Working Groups were replaced by Commissions and Task Groups, the former having the aim of promoting and co-ordinating scientific activity on large themes on a permanent basis, the latter being focussed on temporary problems or on frontier areas of volcanological research" (Gasparini and Johnson, 1995).

In 1995 at the IAVCEI General Assembly in Boulder, USA, and again in revised statutes passed at the 2011 IAVCEI General Assembly in Melbourne, Australia, the concept of individual scientists becoming "affiliates" of IAVCEI and making "donations" were introduced. At the 2015 IAVCEI General Assembly in Prague, Czech Republic, the concept of membership for scientists from all countries, involving fee payment, was included in revised statutes, which are available on the IAVCEI website: https://www.iavceivolcano.org/about-iavcei/statute-and-by-laws.html (last access: 11 July 2018).

4 IAVCEI major conferences, locations and years

IAVCEI has organised major conferences since 1922, interrupted only during World War II, and now has three regular major conferences.

4.1 General assemblies

Since 1922, IAVCEI's general assemblies have been held in conjunction with the IUGG general assemblies. General assemblies serve as both scientific research meetings where new research is presented in a series of symposia and workshops and as business meetings where new committees are inducted and awards for research excellence are presented and celebrated. GAs also allow for joint interdisciplinary research symposia with other IUGG associations. The timing, locations and known numbers of delegates from all IUGG associations attending the IAVCEI–IUGG general assemblies can be found in the Supplement.

4.2 Scientific assemblies

IAVCEI's scientific assembly conferences, which occur between the general assemblies, seem to have only commenced in 1977 and have been held roughly every 4 years since then (see the Supplement for the timing, locations and known numbers of delegates). At scientific assemblies IAVCEI organises an in-house stand-alone scientific conference with emphasis on research, including a celebration of research achievements through presentation of research awards. In addition, there have been some "irregular" meetings, called Volcanological Congresses, which are also listed with scientific assemblies.

4.3 Cities on Volcanoes conferences

IAVCEI's Commission on Cities and Volcanoes has now organised 10 CoV conferences. These tend to cater more to consideration of volcanic hazard, eruption monitoring and civil response issues than the general and scientific assemblies (see the Supplement for the timing, and locations of CoV conferences). In addition, IAVCEI research commissions have organised many other conferences, workshops and field workshops all over the world, making IAVCEI one of the most active associations in IUGG.

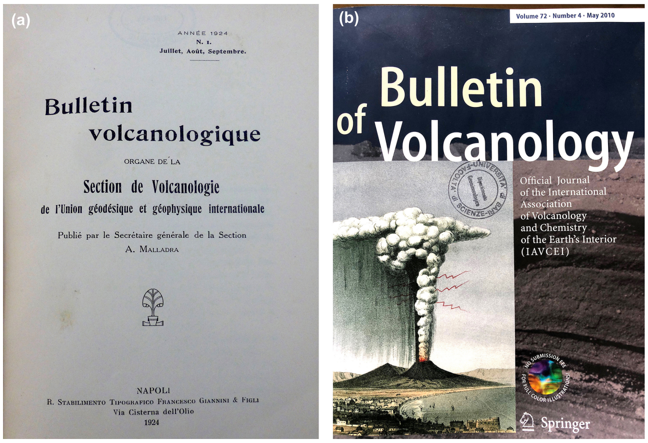

Figure 2. Two versions of the cover of *BV*. **(a)** Volume 1, no. 1, from July–September 1924. **(b)** Cover design from last hard-copy version of *BV*, this issue being Volume 72, no. 4, 2010.

5 *Bulletin volcanologique* and *Bulletin of Volcanology*

5.1 Origin and history

Since very early in its history, IAVCEI has produced its own journal, called *Bulletin volcanologique,* from 1924 to 1984, renamed the *Bulletin of Volcanology* from 1986 on. The first volumes were released spasmodically, and in a confusing manner, in two series. Volume I, series I, has eight issues and/or parts, six of which were released over 2 years in 1924–1925 (Fig. 2), and the last, issue 8, was released in 1931. However, there is some discrepancy in published dates on the *Bulletin of Volcanology* website of Springer, which does not include original journal covers. The break from 1931 to 1937 presumably represents the impact of the Great Depression of the late 1920s and early 1930s, with series II beginning in 1937. Volumes 3 and 4 (of series II) were published in 1938, volume 5 in 1939, and volumes 6 and 7 in 1940, which is when World War II was well under way (continuing until 1945); during this period no volumes of *BV* were published. The first post-World War II volume appeared in 1949 (Volume 8), and *BV* has been published more or less continuously since. No volume numbers were, however, skipped; their publication was just delayed. The covers of post-World War II volumes are labelled Series II, suggesting that after the initial volume I (series I, 1924–1936), the clock was reset in 1937 with the commencement of series II, beginning with another volume 1.

The source of funding to support publication of *BV* in the early years is unclear, but in the 1950s to early 1960s funding was provided by UNESCO, and then during the 1960s and 1970s, it was provided by the National Research Council of Italy, as acknowledged on the covers of *BV*. From the mid-1980s, after publication was handed over to Springer in Germany, funding was provided by IAVCEI and also sourced from journal subscriptions, which continues to the present.

For over 40 years, from 1924 to 1966, the secretary-general was also the editor of *BV*. Up until 1986 the editors were all Italian, but after 1986 scientists from other countries became editors of *BV*. In 1975, at the IAVCEI General Assembly in Grenoble, France, it was decided that the processes by which *BV* was produced needed to be more rigorous, so a more inclusive international peer review process for research papers was established, with Volume 39 in 1976, edited by Franco Barberi and F. Esu Cugusi, being the first output under this new regime. It is unclear how the reviewing of papers prior to this was undertaken, but it was presumably largely done by the editor. Dissatisfaction amongst the IAVCEI community with the slowness of reviewing and processing of papers and publication of research papers came to a head in the mid-1980s, and a decision was made to transfer publication of *BV* to Springer in Germany, coinciding with the appointment of the first non-Italian editor of *BV*, Hans-Ulrich Schmincke, who was also the secretary-general at the time and was instrumental in the change in direction.

In 1986 *BV* was renamed *Bulletin of Volcanology*, was redesigned, took on a new look with the release of Volume 48 and has been continuously produced as a high-quality international journal since. From time to time its format has been revised and refreshed by each new editor. *BV* is now one of the two mainstream international volcanological journals, the other being the *Journal of Volcanology and Geothermal Research* (published by the independent, commercial science publisher Elsevier), which was initiated in the 1970s as a result of dissatisfaction in the international volcanological community with the processes and timescales associated with *BV* at the time. Other journals with a focus on volcanology have also emerged more recently (e.g. the *the Journal of Applied Volcanology and Frontiers in Earth Sciences*).

5.2 Editors of *Bulletin volcanologique* and *Bulletin of Volcanology*

These are the unsung heroes of IAVCEI. Their efforts, as volunteers, in managing the publication of research by the volcanological community on behalf of IAVCEI have long been undervalued. Until this compilation, IAVCEI did not even have a consolidated record of the who editors of *BV* were. The following were editors of *BV* during its history:

- Alessandro Malladra (Italy; also SG; 1924–1936)
- Francesco Signore (Italy; also SG; 1936–1959)
- Francesco Penta (Italy; also SG; 1959–1966)
- F. Esu Cugusi (Italy) – G. Marinelli (Italy; 1967)
- F. Esu Cugusi (Italy) – (Italy; 1968–1975)
- Franco Barberi (Italy) – F. Esu Cugusi (Italy; 1976–1984)

– Hans-Ulrich Schmincke (Germany; also SG) – Steve Sparks (UK; 1986–1989)

– Hans-Ulrich Schmincke (Germany; also SG) – Gail Mahood (USA; 1990–1992)

– Hans-Ulrich Schmincke (Germany; also SG; 1993–1995)

– Don Swanson (USA) – Chris Newhall (USA; 1996–1999)

– Tim Druitt (France) – Jean-François Lénat (France; 2000–2003)

– John Stix (Canada) - Jean-François Lénat (France; 2004)

– John Stix (Canada) – JR Clark (Canada; 2005–2010)

– James White (New Zealand) – Linda White (New Zealand; 2011–2016)

– Andrew Harris (France) – Frances van Wyk de Vries (France; 2017–date of publication).

In addition, the countless members of the editorial board and reviewers of *BV* over the years are acknowledged with thanks.

5.3 Publishers of *Bulletin volcanologique* and *Bulletin of Volcanology* and years

Bulletin volcanologique was published by Francesco Giannini e Figli in Naples, Italy, from 1924–1984, encompassing volumes 1 to 47; the *Bulletin of Volcanology* has been published by Springer, in Berlin, Germany, from 1986 to present, accounting for volumes 48 to 80.

5.4 From hardback only to digital only

From 1924 to 2013 *BV* was published in hard copy, and in the first part of the 21st century, it was published in both a hard-copy and digital version. From 2013 it became available only in digital form online through the Springer *BV* website or through institutional libraries.

5.5 A snapshot of the changing face of *Bulletin volcanologique* and *Bulletin of Volcanology*

BV has been redesigned numerous times since it was first published in 1924. The following are just some of the incarnations of the cover (Fig. 2).

6 *Catalogue of the Active Volcanoes of the World* and *Bulletin of Volcanic Eruptions*

An initial aim of IAVCEI when it was first formed in 1919–1922 was to establish a record of all the known active volcanoes around the world (Gasparini and Johnson, 1995). However, little was done until 1947, when William Q. Kennedy (UK) and James E. Richey (UK) published a first attempt to catalogue and produce a map of the volcanoes of the world as a supplement in Volume 7 of *Bulletin volcanologique* (Kennedy and Richey, 1947). At the 1948 IAVCEI General Assembly in Oslo, Norway, it was decided to build on the database of the catalogue and map of the volcanoes of the world produced in 1947 by subdividing the world into 19 regions, with the aim of producing a catalogue for each, under the editorship of Neumann van Padang (Gasparini and Johnson, 1995). These were published through the IAV–*Bulletin volcanologique* bureau in Naples, Italy, and between 1951 and 1975, 22 volumes were produced.

Part	Region	Year
1	Indonesia	1951
2	Philippine Islands	1953
3	Hawaiian Islands	1955
4	Africa and the Red Sea	1967
5	Melanesia	1957
6	Central America	1956
7	Kuril Islands	1959
8	Kamchatka and continental Asia	1959
9	United States	1959
10	Antarctica	1960
11	Japan, Taiwan and Mariana Islands	1962
12	Colombia, Ecuador and Peru	1966
13	Kermadec Islands and Tonga and Samoa	1959
14	Archipélago de Colón, San Félix Island and Juan Fernández Islands	1962
15	Chile	1962
16	Arabia and Indian Ocean	1963
17	Turkey and the Caucasus	1964
18	Italy	1964
19	Greece	1962
20	New Zealand	1975
21	Atlantic Ocean	1967
22	West Indies	1966

Subsequently, the United States Geological Survey has produced a catalogue of historically active volcanoes of Alaska (Miller et al., 1998).

Up until 1975 all reports of volcanic activity were published by national museum of the Smithsonian Institute as a monthly bulletin, *SEAN* (Scientific Event Alert Network), and later as the monthly *Bulletin of Global Volcanism Network*. The Smithsonian Institution Museum for Natural Science has also produced three editions of their "Volcanoes of the World" series, edited by the following individuals:

- Tom Simkin, Lee Siebert, L. McClelland, D. Bridge, Chris Newhall and John Latter (1981)

- Tom Simkin, Lee Siebert and L. McClelland (1994)

- Lee Siebert, Tom Simkin and Paul Kimberly (2011).

These represent the periodic summaries of those monthly reports under the Global Volcanism Program. The information is summarised and organised as visible data archives online (https://volcano.si.edu, last access: 11 July 2018).

The Smithsonian Institution Museum of Natural History also now provides a constantly updated online catalogue of volcanoes of the world through their Global Volcanism Program (GVP; https://volcano.si.edu/) that can be searched. For each volcano, there is a record of eruptions, reports, a location map and images. The website also provides an up-to-date list of current eruptions.

In 1961 the Volcanological Society of Japan undertook a programme to record annually the eruptions and locations for each year by collecting the data on eruptions from volcano observatories around the world. Their reports were appended to volumes of *Bulletin volcanologique*. At least 33 volumes were produced up to 1994.

In addition, the Smithsonian Institution GVP, in collaboration with the United States Geological Survey, Arizona State University, Portland State University and IAVCEI, releases a weekly email report (VOLCANO: Smithsonian–USGS Weekly Volcanic Activity Report) that summarises the activity level, eruption events and crisis management status for volcanoes worldwide that are currently active or in a state of unrest. This report is distributed through an email news service called Volcano Listserv, which was initiated by Arizona State University under the stewardship of Jonathan Fink in 1984. It continues to provide this service to the volcanological community through the collaboration of the organisations mentioned and also through disseminating information about meetings and news raised by members.

7 IAVCEI newsletter

In addition to *Bulletin of Volcanology*, IAVCEI has had a newsletter for several decades that was initially sent to members through the mail but is now released on the IAVCEI website every 3 to 4 months. *IAVCEI News* summarises past, current and future activities of IAVCEI, including conferences, workshops, and the activities of commissions. It also acts as a forum for raising issues affecting IAVCEI and its membership. The current editor of the *IAVCEI News* is Karoly Nemeth, from Massey University, New Zealand, who was instrumental in refreshing the newsletter when he became editor in 2011. Prior to this the newsletter was largely prepared by the secretaries-general and assistants.

8 IAVCEI Research Commissions, working groups and task groups

Research commissions are now an integral part of the fabric of all IUGG Associations. They consist of groups of scientists who have a common interest in a particular research theme or problem. IAVCEI has a large number of commissions, most of whom are active, organising their own workshops and symposia as parts of IAVCEI's major conferences as well as independently between IAVCEI's major conferences.

Prior to the advent of research commissions in 1979, IAVCEI had rigid sections from 1960 to 1967, covering the fields of active volcanoes, volcano-physics, physics and chemistry of magmas, and paleovolcanology (Gasparini and Johnson, 1995). In 1967, when IAV became IAVCEI, more flexible working groups on topical research themes were introduced to replace sections, and these were changed to commissions and task groups in 1979. According to Gasparini and Johnson (1995), the aim of commissions was to promote and coordinate scientific activity on large themes on a permanent basis, whereas task groups would focus "on temporary problems or on frontier areas of volcanological research" over a finite period (Gasparini and Johnson, 1995).

In recent decades, all commissions and working and/or task groups have had a finite life depending on their level of activity, especially the leadership of these groups. Working and/or task groups have addressed specific issues and then ceased to operate (e.g. 2013 to 2015 IAVCEI Task Group on Crisis Protocols, led by Guido Giordano – Italy), which produced guidelines on the responsibilities, roles and liabilities of scientists involved in volcanic event management. Some commissions have become defunct or been decommissioned or resurrected under new leadership after some time of inactivity, and so the nature and themes of commissions have changed. Unfortunately, IAVCEI has not kept records, but an attempt to record the commissions and their leaders in IAVCEI's past is being made and will be summarised when completed on the IAVCEI website and included in IAVCEI's centenary booklet to be released at the 2019 IUGG General Assembly in Montréal, Canada.

One of the first thematic areas of research or investigation (an informal commission or working group) undertaken by IAVCEI when it was first formed was one on submarine volcanism, focussing largely, but not exclusively, on activity in the Indonesian archipelago, then part of the Dutch East Indies. There were regular reports in *Bulletin volcanologique* in a specifically titled section on submarine volcanic activity listed in the contents of the first volumes.

9 Collaboration with other IUGG associations

In addition to collaborating in the organisation of inter-association symposia at each IUGG general assembly, IAVCEI also contributes to activities of the following IUGG Union Commissions:

- Climatic and Environmental Change (CCEC)
- Mathematical Geophysics (CMG)
- Geophysical Risk and Sustainability (GRC)
- Study of the Earth's Deep Interior (SEDI)
- Data and Information (UCDI)
- Planetary Sciences (UCPS).

In addition, it contributes to the activities of the following inter-association commissions:

- Joint Tsunami Commission
- International Heat Flow Commission
- Commission on Physics and Chemistry of Earth Materials
- Commission on Volcano Seismology and Acoustics
- Working Group on Electromagnetic Studies of Earthquake and Volcanoes (EMSEV)
- Commission on Volcano-Ice Interaction.

10 Early career researcher network

In 2013 IAVCEI instigated an early career research network to cater to the needs of postgraduate students, postdoctoral researchers and early career academics in establishing contacts and networks of like minds early in their careers. By engaging with the Early Career Researcher (ECR) Group and giving them a visible status in IAVCEI, the executive committee of IAVCEI wanted to establish a communication link with ECRs to help them develop a better understanding of how engaging in IAVCEI conferences and workshops would be beneficial to their careers. A successful scoping workshop was held at the 2013 Kagoshima IAVCEI General Assembly in Japan, together with another at the 2015 Prague General Assembly in the Czech Republic, followed by an evening ECR dinner to which a number of older scientists were invited as mentors. In 2018, the ECR Network Group has been invited to develop a new logo for IAVCEI, and ECR events are being planned for the 2019 Montreal Centenary General Assembly. The prime movers to help instigate the IAVCEI ECR network were Charlotte Vie (UK) and Sam Poppe (Belgium).

11 IAVCEI awards

In the latter half of its history IAVCEI introduced several awards to recognise outstanding scholarly and professional achievements.

11.1 Wager Medal

The first IAVCEI award, introduced in 1975, was for excellence in research. It was named the Wager Medal after Lawrence Rickard Wager (1904–1965), a petrologist at Oxford University, most famous for his seminal research on the petrological architecture and origins of the massive Skaergaard layered intrusive complex in Greenland. Although originally awarded every 4 years through a collaboration with the Royal Society of London, "the medal is (now) given every two years (i.e. at both Scientific and General Assemblies), to a scientist up to 15 years after Ph.D acquisition, who has made outstanding contributions to volcanology, particularly in the 8-year period prior to the Award" (IAVCEI website). Multiple nominations are usually received in each round. A list of past awardees can be found at the IAVCEI web page: https://www.iavceivolcano.org/iavcei-awards/wager-medal.html (last access: 11 July 2018).

11.2 Thorarinsson Medal

In 1987 IAVCEI introduced the Thorarinsson Medal sponsored by the Geological Society of Iceland. Named after the famous Icelandic volcanologist Sigurdur Thorarinsson (1912–1983), the award is made "every four years at the IAVCEI Scientific Assembly to a scientist of outstanding distinction who has made fundamental contributions to research in volcanology" (IAVCEI website). A list of past awardees can be found at the IAVCEI web page: https://www.iavceivolcano.org/iavcei-awards/thorarinsson-medal.html (last access: 11 July 2018).

11.3 Krafft Medal

The Krafft Medal, introduced in 2004, is named after the French husband-and-wife team Maurice and Katia Krafft, who were tragically killed by a block and ash flow during an eruption of Mount Unzen in Japan in 1991, together with another volcanologist, Harry Glicken, and 40 people from the media. The medal is sponsored through a trust fund established by the Krafft family and "is awarded every 4 years at the IAVCEI Scientific Assembly to an individual who has made outstanding contributions to volcanology through service to the scientific community or to communities threatened by volcanic activity. The Krafft Medal honours those who have shown altruism and dedication to the humanitarian and applied sides of volcanology and those who have made selfless contributions to the volcanological community" (IAVCEI website). A list of past awardees can be found at the IAVCEI web page: https://www.iavceivolcano.org/iavcei-awards/krafft-medal.html (last access: 11 July 2018).

11.4 George Walker Award

This award honours George P. L. Walker, originally from the UK, whose largely field-based research modernised and pioneered a quantitative approach to understanding volcanic eruptions, especially explosive eruptions. The award was introduced in 2004 and "is given every two years to a scientist up to 7 years after Ph.D acquisition. The award recognises achievements of a recent outstanding graduate in the fields of research encompassed by IAVCEI, or also a recent graduate whose achievements in volcanology involved operating in difficult circumstances" (IAVCEI website, 2018). The award is sponsored from a trust fund established by the Walker family. A list of past awardees can be found at the IAVCEI web page: https://www.iavceivolcano.org/iavcei-awards/george-walker-medal.html (last access: 11 July 2018)

11.5 The Fisher Medal

The Fisher Medal is in honour of Richard V. Fisher (1928–2002), who made major contributions to understanding the behaviour of pyroclastic density currents, based largely on field studies of their deposits: "The medal is given every 4 years at the IAVCEI Scientific Assembly to a scientist who has made outstanding contributions to volcanology based primarily upon field observations" (IAVCEI website). The medal was introduced in 2017. More information can be found at https://www.iavceivolcano.org/iavcei-awards/fisher-medal.html (last access: 11 July 2018).

11.6 Volcanic Surveillance and Crisis Management Award

The Volcanic Surveillance and Crisis Management Award honours the personnel from institutions or organisations responsible for monitoring volcanoes (volcano observatories and/or other institutions) that have made a remarkable contribution to the mitigation of volcanic hazards and volcanic risks. Volcano monitoring, eruption forecasting and the mitigation of volcanic hazards are key objectives of volcanologists and a duty of volcano observatories worldwide. Criteria for eligibility include the following: successful hazard assessment and mitigation efforts, effective volcano surveillance and eruption forecasting, and/or effective crisis management: "This award will be presented every 2 years at the Cities on Volcanoes Meeting (CoVs)" (IAVCEI website). The first award was given in 2018 (https://www.iavceivolcano.org/iavcei-awards/volcano-surveillance-and-crisis-management-award.html (last access: 11 July 2018)).

12 IAVCEI Decade Volcanoes programme

The United Nations declared 1990–2000 to be the International Decade for Natural Disaster Reduction. IAVCEI identified 16 volcanoes worldwide to be the focus of studies for the IAVCEI Decade Volcanoes programme (https://en.wikipedia.org/wiki/Decade_Volcanoes (last access: 11 July 2018)). The criteria for choosing these volcanoes included relatively recent eruptive activity, multiple potential hazards, proximity to centres of population, high risk levels to the population in the event of eruptions, reasonable access for study, and support from local scientific and government instrumentalities. IAVCEI had hoped that funding would be made available from the United Nations, but this did not eventuate. Most studies were funded by national research organisations and through international collaborative aid programmes. Not surprisingly some volcanoes received greater attention than others, depending on resources available. The 16 Decade Volcanoes selected were the following.

Volcano	Region	Country
Avachinsky – Koryaksky	Kamchatka	Russia
Colima	Jalisco	Mexico
Galeras	Nariño	Colombia
Mauna Loa	Hawaii	United States
Mount Etna	Sicily	Italy
Mount Merapi	Central Java	Indonesia
Mount Nyiragongo	North Kivu	Democratic Republic of the Congo
Mount Rainier	Washington	United States
Mount Vesuvius	Campania	Italy
Mount Unzen	Nagasaki – Kumamoto	Japan
Sakurajima	Kagoshima	Japan
Santa María	Quetzaltenango	Guatemala
Santorini	South Aegean	Greece
Taal Volcano	Calabarzon	Philippines
Teide	Canary Islands	Spain
Ulawun	East New Britain – West New Britain	Papua New Guinea

A number of these volcanoes have been volcanically active since being declared Decade Volcanoes, including Avachinsky (1991, 2002; Smithsonian Institute Global Volcanism Program – SI GVP – website, 2018); the Koryaksky volcano (2009; SI GVP); Colima (many times); Galeras in 1993, when six scientists (during Decade Volcanoes workshop) and two tourists were killed; Etna (many times); and Merapi (many times). The Nyiragongo volcano in the Congo had erupted catastrophically in 1977, involving extremely fastflowing lava that killed 70 people. It experienced another eruption in 1994, during the civil war there, and then another large eruption in 2002, which again produced far-flowing lavas that inundated Goma and killed ~ 150 people due to CO_2 asphyxiation and collapsed buildings. Mount Unzen underwent a 4-year-long eruption from 1991–1995 (see above), and Sakurajima has been almost constantly active, marked by frequent, spaced vulcanian explosions. The Santa María volcano has also been frequently active, and both Santorini and Teide have experienced seismic crises without an eruption occurring. The Ulawun volcano is frequently active and is notable for its very high emissions of SO_2.

Data availability. The data that is presented in this paper and in the supplementary file have been sourced from the cited references, as well as from non-cited, generic sources (i.e. without specific authors identifiable) that are not available in digital form and therefore do not have accessible URLs. In particular, the following sources were used to identify, where possible, the names and years of service of past IAVCEI presidents, secretaries-general, committee members, and editors of *Bulletin volcanologique* (*Bv*) and *Bulletin of Volcanology* (*BV*).

The names of IAVCEI presidents and secretaries-general are listed on the IAVCEI website (https://www.iavceivolcano.org/, last access; 11 July 2018). Finding information about IAVCEI committee members and editors of *Bv* and *BV* was more difficult. Sourcing information about these from *Bv* and *BV* required accessing old hard copies of the journals from 1924 to 1986 because the digitised copies of these journals available on the *BV* website do not contain scanned copies of the original hard covers of the journal issues on which the names of the editors of *Bv* and *BV*, and sometimes the IAVCEI president and secretary-general and committee members, are listed. In addition to accessing old hard copies of *Bv* and *BV*, copies of the IUGG Yearbook from 2004–2018 were used. These were formerly available in digital form online on the IUGG website but are no longer available there. In addition, *IUGG Chronicles* (1975, p. 313–315; 1976, p. 461–463; 1978, p. 216–218; 1980, p. 295–297; 1983, p. 50–52; 1989, p. 138–241; 1992, p. 238–240; 1995, p. 68–72, 298–299) and *IUGG Comptes Rendus* (1968, p. 206–208; 1975, p. 313–315) were also used.

Information about the IAVCEI Decade Volcanoes research initiative was sourced using: Wikimedia Commons Decade Volcanoes: https://upload.wikimedia.org/wikipedia/commons/4/42/WikiReader_Decade_Volcanoes (last access: 11 July 2018). pdf and Wikipedia Decade Volcanoes: https://en.wikipedia.org/wiki/Decade_Volcanoes (last access: 11 July 2018). Information about each Decade volcano is available on the website of the Smithsonian Institution Global Volcanism Program: https://volcano.si.edu/ (last access: 11 July 2018).

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/hgss-10-181-2019-supplement.

Author contributions. Raymond A. F. Cas was president of IAVCEI from 2011–2015 and is currently a member of the executive committee of IAVCEI, 2015–2019. He is an emeritus professor at Monash University in Melbourne, Australia, and an honorary adjunct professor at the University of Tasmania in Hobart, Australia. This work is his, and all sources of information have been cited and acknowledged.

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