



The Maturation of Scientific Evidence of Anthropogenic Climate Change

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Abstract. With respect to anthropogenic climate change, the question of who knew what when is of growing legal significance, as jurisdictions take up questions of climate legal liability. Yet despite an enormous volume of scientific literature and recurring expert assessments, no concise account traces what we know about anthropogenic climate change, how we know it, and when the evidence of it became mature. By “mature” we mean an evidence base that is methodologically standardised, institutionally sustained, and independently cross-validated across multiple instruments and groups. Existing syntheses, whether multi-volume assessment reports, detailed monographs, or consensus analyses, do not provide this information in a form accessible to non-specialist professional audiences. This review assembles such a maturation timeline. For each of the four major indicators of climate change – temperature, sea level, greenhouse gases, and cryosphere (ice sheets, glaciers, snow cover, and permafrost) – we trace the progression of expert knowledge. Typically, it starts with isolated, sometimes idiosyncratic observations, and then goes through methodological standardisation and national institutionalisation, eventually turning into coordinated international observing systems. By presenting these developments side by side, we show that the principal observational pillars of climate science developed into internationally standardised, independently cross-validated evidence bases between the mid-twentieth and the early twenty-first centuries. These observations, combined with climate model simulations of what the world would have been like without human intervention, constitute the empirical foundation of the modern scientific case for anthropogenic climate change, as well as the potential ethical and legal case for climate liability. This latter consideration has gained relevance since the International Court of Justice – in its 2025 advisory on the obligations of states in respect of climate change – affirmed the scientific record as central to establishing breach of international environmental law.

1 Introduction

It is now well established that anthropogenic climate change is underway and has been for several decades. In 1995, the Intergovernmental Panel on Climate Change (IPCC), in its *Second Assessment Report*, stated that “the balance of evidence” suggested a “discernible” human impact on the climate system (IPCC, 1995). Subsequent



reports have strengthened and extended this claim, including specific aspects of the climate system, such as heat waves, heavy precipitation, and sea level rise. The *Third Assessment Report* concluded that “most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations” (IPCC, 2001); the Fourth, that “most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations” (IPCC, 2007); and the Fifth, that “it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century” (IPCC, 2013). For its central conclusion, the Sixth Assessment dispensed with likelihood qualifiers: “It is unequivocal that human influence has warmed the atmosphere, ocean and land” (IPCC, 2021). The evidence behind these increasingly confident statements is the subject of this paper. Yet, a basic question about climate change remains surprisingly difficult to answer clearly: when did each principal line of observational evidence become mature, and how did initially local, even idiosyncratic, measurements coalesce into the globally coordinated monitoring systems on which contemporary climate science depends?

The question is not merely historical. For educators and students entering the field, understanding when key indicators became reliable clarifies which claims rest on decades of corroborated data and which remain subjects of active refinement or even debate. For policymakers assessing the adequacy of past and present action, the timeline of scientific knowledge delimits what was knowable, and therefore foreseeable, at any given moment. For legal practitioners, the answers to questions of state obligation, corporate foreseeability, due diligence, and potential liability rest in significant part on the temporal structure of the evidence base, including which actors had access to, or reasonably should have understood, that evidence at any given time (Stuart-Smith et al., 2021; Peel and Osofsky, 2015). Climate litigation now encompasses approximately 3,000 cases across some 60 jurisdictions worldwide (Setzer and Higham, 2025). The relevance of this audience has sharpened considerably since the International Court of Justice – in its advisory opinion of 23 July 2025 on the obligations of states in respect of climate change – affirmed the scientific record as central to establishing breach of international environmental law (International Court of Justice, 2025).

However, tracing that record is difficult: the relevant sources are vast, heterogeneous, and dispersed. Contemporary climate science encompasses hundreds of thousands of peer-reviewed articles, technical annexes, model-intercomparison exercises, and national and international assessments. The IPCC Sixth Assessment Report exemplifies the scale: its Working Group I contribution (The Physical Science Basis) alone runs to roughly 2,500 pages, and it assesses more than 14,000 scientific publications (IPCC, 2021). The full assessment across three Working Groups exceeds 8,000 pages. As several historians and analysts of climate knowledge have observed for some time, it is nearly impossible for any individual, including domain experts, to command more than a fraction of this huge, fragmented and difficult-to-navigate body of information (Weart, 2008; Edwards, 2010; Fleming, 2020), and in recent years the challenge has only worsened.

The IPCC exists to assess this literature – to synthesise, evaluate, and judge it – but it is not structured to answer the temporal question. IPCC reports are extensive multi-volume compilations; even the *Summaries for Policymakers*



are lengthy and technically dense. The resulting documents present what is known and at what confidence level, but they are not designed to explain how we came to know it, nor to trace when different components of the scientific picture matured. They assemble convergent lines of evidence yet devote limited attention to an epistemic overview that follows the construction of core physical-science claims over time.

Existing historical scholarship is organised by intellectual theme or institutional infrastructure. Rich narrative histories have been written by Weart (2008), Edwards (2010), Howe (2014), Fleming (2020), and Oreskes (2021), but none presents the observational record in a concise, data-anchored format. The IPCC’s own historical overview (Le Treut et al., 2007) traces the development of climate science thematically – across the growth of physical understanding, the development of climate models, and the institutional history of the assessments – but it is organised around the maturation of conceptual understanding rather than the observational record, and, completed in 2007, it necessarily omits developments since then. Recent annual indicator updates (e.g. Forster et al., 2024, 2025), track the current state of the climate system in near-real time, but their purpose is contemporary monitoring rather than historical reconstruction of the evidence base.

This paper traces the physical-science evidence base for climate change as it matured over the twentieth and early twenty-first centuries. Maturity, in the sense used here, is a property of an observing system rather than of any single result. We examine four families of widely recognised climate-change indicators: energy balance, cryospheric change, sea level and greenhouse-gas concentrations. We performed a comprehensive review of academic literature using IPCC reports as a starting point, to trace how each set of indicators progressed from mostly isolated observations to standardised, internationally coordinated measurement systems.

The individual timelines are discussed in the following sections. In Fig. 5, we compiled them together into the timeline of the maturation of scientific evidence of anthropogenic climate change.

Our focus is on observational evidence of climate change; we do not survey the literature on impacts, vulnerabilities, or socio-economic futures. Nor do we address climate modelling except where model–observation comparisons are integral to the evidentiary narrative. Formal attribution is itself such a model–observation comparison, and we cover those comparisons where they bear on when an indicator’s change became detectable and attributable; we do not attempt a survey of climate modelling as a field.

2 Timelines

We examine four domains of widely recognised climate-change indicators. Although these indicators are closely interconnected, for the purposes of this review we group them according to the dominant physical processes they represent.

Throughout, “forcing” refers to an influence imposed on part of the climate system from outside it, driving that part away from equilibrium. Here it is the heat that seawater delivers to ice-sheet margins; later it is the change in Earth’s radiation balance produced by greenhouse gases, aerosols, volcanic eruptions, or changes in solar output.



The first domain concerns Earth’s energy balance, mostly measured through temperature, including surface, atmospheric, and oceanic records. The second focuses on the cryosphere, whose response to warming – through melting, de-stabilisation, retreat – is visually apparent and was one of the earliest indicators to be widely recognized. For fast-responding components such as sea ice, glaciers, and snow cover this response is tightly and nearly linearly coupled to temperature; for the great ice sheets it is more loosely coupled, paced by ocean forcing and slow, nonlinear ice dynamics that can lag changes in air temperature by decades to millennia. The third covers sea-level rise, a combined result of thermal expansion of seawater and the melting of terrestrial ice. The fourth covers greenhouse gases, which constitute the principal driver of anthropogenic climate change and provide essential, long-term evidence of its causes. We present the domains in the order in which their evidence bases matured rather than by causal priority: although greenhouse gases are the principal physical driver, and although cryospheric change was among the first to be noticed, the instrumental temperature record was the earliest to be placed on a systematic, quantitative footing, so we begin with the energy balance.

2.1 Temperature

Temperature is arguably the most recognisable indicator of climate change and “global warming”. The graphs in Fig. 1 represent a compilation of the major sources of information. They clearly show increases in terrestrial and ocean temperature over the course of the 20th century, a decrease in stratospheric temperature (consistent with greenhouse-gas heat trapping in the troposphere), and an overall increase in the total Earth “heat inventory”.

2.1.1 Surface Air Temperature

The Central England Temperature (CET) series, now widely used as a benchmark, is not a continuous record but rather a twentieth-century reconstruction, combining heterogeneous thermometer records converted into a homogenised set expressed in degrees Celsius. The monthly CET series were reconstructed from several sites and observers beginning in 1659 (Manley, 1974) and a daily CET series starting in 1772, when the underlying observations became more consistently instrumental (Parker et al., 1992; Parker, 2010a).

From the late seventeenth century, observers in Europe kept weather diaries, which often included temperature measurements of various kinds (Middleton, 1966; Anderson, 2005; Chang, 2004). In the eighteenth century, dedicated observatories began to appear as state responsibilities. In 1854, the UK’s Met Office was founded, and in 1855 the French national meteorological service followed at the Paris Observatory. In 1873, the non-governmental International Meteorological Organization (IMO) was established, and in 1950 it was transformed into the intergovernmental World Meteorological Organization (WMO) (Zillman, 2018).

From the late 1800s, collaborations drove standardisation in both exposure and instrumentation. The Stevenson screen, a white, louvred wooden box placed at a standard height over grass, was widely adopted, providing a reference environment for “air temperature in the shade” and reducing biases from direct radiation and local surroundings (Parker, 1994). Telegraphic communication allowed simultaneous reporting, so readings taken for daily weather

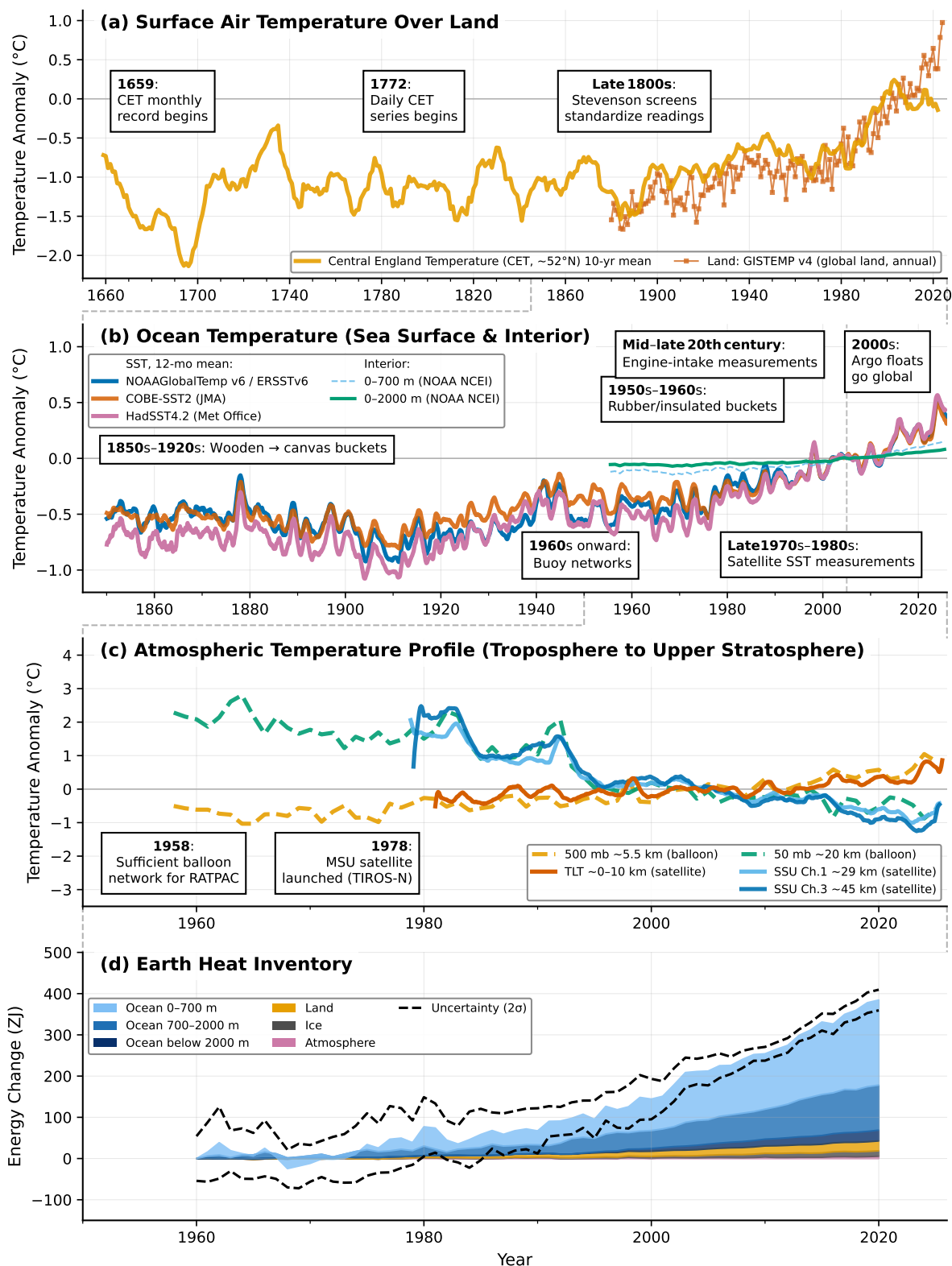




Figure 1. Temperature anomalies across the climate system (temperature panels relative to a 1991–2020 baseline; the Earth heat inventory panel shows cumulative energy change since 1960). **(a)** Land surface air temperature, with the Central England Temperature (CET, $\sim 52^\circ\text{N}$) 10-year running mean from 1659 onward and GISTEMP v4 global land annual data; annotations mark the start of the CET monthly record (1659), the daily CET series (1772), and the late-1800s introduction of Stevenson screens. **(b)** Ocean temperature, combining three methodologically distinct sea-surface temperature products shown as 12-month running means – NOAA GlobalTemp v6 (using ERSSTv6), HadSST4.2 (Met Office Hadley Centre), and COBE-SST2 (Japan Meteorological Agency) – with NOAA NCEI ocean interior vertical-mean temperature for 0–700 m (dashed) and 0–2000 m (solid, ± 1 standard error (SE) shading); a dashed vertical line marks the onset of global Argo float coverage (~ 2005). **(c)** Atmospheric temperature profile from troposphere to upper stratosphere, with RATPAC-A radiosonde data at 500 mb (~ 5.5 km, lower troposphere) and 50 mb (~ 20 km, lower stratosphere) shown dashed, NOAA STAR TLT satellite for the lower troposphere (~ 0 –10 km), and NOAA STAR merged SSU/AMSU-A channels 1 (~ 28 km) and 3 (~ 45 km) for the mid- and upper stratosphere shown solid; the contrasting tropospheric warming and stratospheric cooling is a key fingerprint of human influence. Stratospheric cooling, however, has two distinguishable anthropogenic drivers with different altitude signatures: well-mixed greenhouse gases (chiefly CO_2), which cool the entire stratosphere and dominate the cooling of the upper stratosphere, and ozone depletion, which was the major cause of cooling in the lower stratosphere (near the 50 mb level shown here) from the late 1970s to the mid-to-late 1990s. Isolating the ozone-driven cooling from the greenhouse-gas signal was an essential step in attribution: Ramaswamy et al. (1996) showed that observed ozone losses leave a distinct spatial and seasonal fingerprint in lower-stratospheric cooling, which had to be separated from the well-mixed-gas signal before the residual could be attributed to CO_2 (Santer et al., 2013, 2023). The later stabilisation of ozone under the Montreal Protocol – after which lower-stratospheric temperature has been near-constant while CO_2 -driven cooling continued aloft (about 0.25 to 0.4°C per decade since 1998, against 0.5 to 0.6°C per decade over 1979–2015 as a whole) – confirms that separation and is itself visible in the SSU/AMSU-A records shown. **(d)** Earth heat inventory (1960–2020) from GCOS (von Schuckmann et al., 2023) as a stacked area chart in zettajoules across ocean layers (0–700 m, 700–2000 m, below 2000 m), land, ice, and atmosphere, with 2σ uncertainty bounds.

125 maps accumulated in institutional archives. The Bergen School, founded by Vilhelm Bjerknes in 1917, for instance, built its frontal and air-mass analysis on these dense, coordinated observations (Friedman, 1993). In the twentieth century, these archives were digitised and homogenised, with corrections for station moves, instrument changes, and urbanisation, and then combined into gridded global land-surface temperature series used today (Hansen et al., 2010; Morice et al., 2021). The estimates of global land temperature change were created as products of gridded global
 130 land-surface temperature series, such as the GISTEMP created and maintained by NASA’s Goddard Institute for Space Studies in late 1970s (Lenssen et al., 2024). The first synthesis intended to be global rather than hemispheric followed in 1986, when homogenised land and marine data for both hemispheres were combined into a single mean series covering 1861 to 1984 (Jones et al., 1986); an independently constructed station-based analysis published the following year agreed with it on the century-scale trend (Hansen and Lebedeff, 1987). Agreement between series



135 built by different groups from different station selections, rather than the length of any one of them, is what made the global surface record usable for trend detection.

In the 1990s, the adequacy of corrections for urbanisation became the focus of a public controversy. It is the claim that the observed warming was largely an artefact of the urban heat island (UHI), i.e. thermometers progressively engulfed by growing cities rather than recording a genuine climatic signal. The rural-station comparisons from the mid-1980s through the 1990s allowed this hypothesis to be tested. Jones et al. (1990) found the urbanisation influence in two of the most widely used hemispheric records to be at most an order of magnitude smaller than the century-scale warming. Peterson et al. (1999) found that the 2,290 stations classified as rural in the 7,280-station global network showed, if anything, slightly greater warming than the network as a whole (0.70 versus 0.65°C per century over 1880–1998). By January 1999 *Science*'s news pages were reporting that the debate had subsided (Irion, 1999), but it reignited in the mid-2000s, centred on station siting and adjustment practices. However, a second round of tests reached the same verdict: that global warming was real, and not an artifact of the heat island effect. Noting that the UHI is strongest on calm, clear nights and is suppressed by wind, Parker (2004; Parker, 2006), compared land-temperature trends on windy versus calm nights worldwide and found them essentially identical. Reconstructions by the Berkeley Earth project isolated rural stations and found the urban influence on the global land trend statistically indistinguishable from zero, and if anything slightly negative (Wickham et al., 2013; Muller et al., 2013).

In the US network, urbanisation imparts a measurable warm bias to the raw records, but the homogenisation procedure removes it – and the homogenised series has since been shown to reproduce the trend of a deliberately rural, pristinely sited reference network (Hausfather et al., 2013, 2016). The IPCC accordingly judges it unlikely that residual urbanisation has raised the global land-mean trend by more than about ten per cent (Gulev et al., 2021), even as the UHI remains a substantial signal within individual cities. This episode of a contrarian hypothesis being tested directly reinforces confidence in the instrumental record (Parker, 2010b).

The GISTEMP record does not extend as far back in time as the CET series (Fig. 1), because estimating a global temperature requires a sufficiently large number of geographically dispersed stations, which only became available from the nineteenth century onward. Because land warms roughly 1.8 times faster than the ocean surface in the global mean (1.59°C over land against 0.88°C over the ocean from 1850–1900 to 2011–2020; IPCC, 2021), the land-only trends shown here are larger than the combined land-and-ocean global mean surface temperature used in IPCC assessments and the Paris Agreement targets. The combined metric, available from 1850 in HadCRUT5, Berkeley Earth, and the U.S. National Oceanic and Atmospheric Administration's (NOAA) GlobalTemp v6, provides the globally representative baseline against which policy thresholds are defined. They show that, overall, mean global temperature has warmed by about 1.1°C since 1880. This figure reflects the long-term trend – the slope of a regression fitted across the record (or, equivalently, the difference between multi-decadal period averages) – rather than the difference between two individual years, because single-year values are strongly affected by short-term variability



such as El Niño and post-volcanic cooling. The rate of warming has itself accelerated, rising from roughly 0.06°C per decade over the full record to about 0.20°C per decade since 1982 (NOAA, 2025b).

2.1.2 Atmospheric temperature

From the 1930s onward, radiosondes – small instrument packages transmitted aloft by balloon – added a vertical dimension to the temperature picture. Early information had come from mountain observatories, and occasional instruments carried by kites and free balloons, but radiosondes transmitted temperature, pressure, and humidity as they rose through the troposphere and into the lower stratosphere (Edwards, 2010). Over time, national weather services established regular radiosonde launch schedules, forming a global network of vertical profiles. Systematic sounding of the free atmosphere is older than the radiosonde. Unmanned self-registering balloons were first launched from Paris in 1892, and in 1898 Léon Teisserenc de Bort founded a station dedicated to them, the Observatoire de Météorologie Dynamique at Trappes near Versailles, where kites and sounding balloons were flown as a routine programme. In 1902 he presented the results of 236 such soundings and reported a zone isotherme: above an altitude varying between 8 and 12 km, temperature ceased to fall and in places rose slightly (Teisserenc de Bort, 1902; Hoinka, 1997). The boundary is now called the tropopause.

Homogenised upper-air products now trace temperature anomalies from 1958 onward. The Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC) combine station adjustments developed for the 1958–1997 period with data drawn thereafter from the Integrated Global Radiosonde Archive (IGRA) (Free et al., 2005). IGRA itself was assembled in the mid-2000s and brings together upper-air observations from as early as the 1900s, including pilot balloon and kite soundings as well as radiosondes (Durre et al., 2006).

Beginning in 1979, microwave sounding units on NOAA polar-orbiting satellites added near-global coverage that the radiosonde network (concentrated over Northern Hemisphere landmasses) could not provide (Spencer and Christy, 1990). In the lower atmosphere, satellite-derived Lower Troposphere Temperature (TLT) products now complement radiosonde records such as RATPAC, and combined radiosonde–satellite datasets are central to detection and attribution studies. At higher altitudes, the Stratospheric Sounding Unit (SSU) measured temperature-weighted radiances from approximately 28 km to approximately 45 km. Because the original SSU instrument operated only until 2006, a merged SSU+AMSU-A product extends the record to the present, using a variational method that matches both temperatures and weighting functions across the overlap with Advanced Microwave Sounding Unit channels (Zou and Qian, 2016); this yields a continuous mid-to-upper stratospheric temperature record. As Fig. 1 shows, the cooling signal strengthens markedly with altitude: while 50 mb (20 km, lower stratosphere) has cooled by roughly 0.6–0.8°C since 1979, SSU Channel 1 (28 km) shows approximately 1.8°C of cooling and SSU Channel 3 (45 km) shows approximately 2.4°C. Santer et al. (2023) demonstrated that including these upper-stratospheric layers in a multi-layer fingerprint analysis improves the detectability of the anthropogenic signal by approximately a factor of five relative to analyses restricted to the troposphere and lower stratosphere alone.



For two decades the satellite and radiosonde records disagreed about the magnitude, and at times the sign, of tropospheric warming, and that discrepancy became one of the most frequently cited empirical objections to the surface temperature record. Its resolution was largely technical. Correcting the satellite series for the drift of satellite orbits through the diurnal cycle removed a spurious cooling and raised the derived tropospheric trend (Mears and Wentz, 2005), while independent analysis showed that daytime radiosonde measurements carried their own spurious cooling, introduced as instrument packages were improved to reduce solar heating of the sensor (Sherwood et al., 2005). The first synthesis and assessment product of the U.S. Climate Change Science Program concluded in 2006 that the discrepancy no longer existed: for recent decades every current data set showed global-average warming aloft similar to the warming at the surface. The same report was careful to add that discrepancies in the tropics remained to be resolved (U.S. Climate Change Science Program, 2006), and they remain so (Eyring et al., 2021). The residual disagreement is between models and observations rather than between one observing system and another, which is why the record counts as reconciled here in 2006.

The reversed trends between the lower and upper atmosphere visible in Fig. 1c constitute one of the most distinctive signatures of greenhouse warming – sometimes referred to as a “fingerprint” of human causation (Santer et al., 1996). Increased greenhouse-gas concentrations trap outgoing longwave radiation in the troposphere while reducing radiative heating of the stratosphere. This vertical structure cannot be explained neither by solar forcing, which would warm all atmospheric layers, nor by internal variability alone (Santer et al., 1996; Tett et al., 1996). The combination of warming below and strong cooling above, confirmed independently by radiosonde and satellite observations across more than four decades, provided some of the earliest detection-and-attribution evidence linking observed warming to human activities (Karoly, 1989; Santer et al., 1996; Tett et al., 1996; Vinnikov et al., 1996), with the strength of this fingerprint subsequently confirmed and extended into the upper stratosphere (Santer et al., 2023).

2.1.3 Oceanic temperature

Mariners had long known from experience and simple soundings that deeper water could be colder than surface water; ancient authors and early navigators remarked on cold water drawn from depth. But deep-water temperatures were notoriously hard to measure (Oreskes, 2021). Systematic, quantitative measurement of sea temperature began in the nineteenth century and followed two paths: the surface and the vertical profile (Deacon, 2018).

Sea-surface temperature

From the mid-nineteenth century, naval and commercial vessels began to record sea-surface temperature (SST) along their routes for navigation and storm warnings. The standard procedure was to lower a bucket, haul up seawater, and place a thermometer in the bucket. The type of bucket mattered: wooden buckets, common in the nineteenth century, were gradually replaced by lighter canvas buckets, which allowed more evaporation and therefore more cooling of the sample before reading. From about the 1950s, insulated rubber buckets were introduced to reduce this effect. In the mid-twentieth century, many ships switched to using engine-room intake water instead of buckets, sampling water drawn from below the surface into the cooling system, and as ships got larger over time, the intake



pipe got lower, affecting the temperature. Each change solved a practical problem on ships and each altered the bias of the measurements by a few tenths of a degree Celsius. To account for these evolving practices, physically based bias models were developed that are now embedded in SST reconstructions (Folland and Parker, 1995; Kennedy, 2014).

240 From the 1960s, dedicated ocean observing systems developed alongside ship measurements; from the late 1970s, networks of moored and drifting buoys were deployed across major basins, measuring SST and other variables at specified depths and positions. From the early 1980s, satellite radiometers began to provide nearly global maps of sea-surface skin temperature. Combining in situ and satellite data into consistent SST analyses required bias correction of both sensor types – ship intakes read warm relative to drifting buoys, and satellites measure skin rather than bulk
 245 temperature – together with careful treatment of ice-covered regions (Reynolds et al., 2002). By the late twentieth century, SST had become a densely sampled, internationally coordinated variable with quantified uncertainties (Kennedy, 2014; Abraham et al., 2013). Figure 1 illustrates this convergence by displaying three independently constructed SST products: ERSSTv6, produced by NOAA using empirical orthogonal teleconnection interpolation with neural-network enhancements (Huang et al., 2025); COBE-SST2, produced by the Japan Meteorological Agency
 250 using optimal interpolation of ICOADS ship and buoy data (Hirahara et al., 2014); and HadSST4, produced by the UK Met Office using a physics-based bias model without spatial interpolation (Kennedy et al., 2019). These three products draw on overlapping but not identical source data, apply different instrumental and sampling corrections, and are maintained by independent national centres on three continents. That they produce closely consistent warming trends despite these methodological differences is itself an important element of the evidentiary case.

255 *Ocean interior temperature*

From 1872 to 1876, the voyage of *H.M.S. Challenger* – often described as the first global oceanographic expedition – established the foundations of deep-ocean temperature measurement. The *H.M.S. Challenger* circumnavigated the globe, lowering thermometers and sampling bottles at many stations to record temperature and other properties; the multi-volume *Report on the Scientific Results of the Voyage of H.M.S. Challenger* established the existence of
 260 a cold, stratified abyss and global water masses (Challenger Expedition (1872-1876) et al., 1880; Deacon, 2018).

In the late nineteenth century, a more reliable method for measuring deep-ocean temperature emerged with deep-sea reversing thermometers and dedicated sampling bottles. Fridtjof Nansen’s design combined a reversing thermometer with a metal water bottle that was lowered open and then flipped at depth, simultaneously sealing the bottle and locking in the temperature reading. Arrays of Nansen bottles and reversing thermometers became
 265 standard oceanographic tools through the first half of the twentieth century; their use is well documented in later reviews (McConnell, 1982; Rozwadowski and Van Keuren, 2004).

From the 1950s onward, mechanical bathythermographs (MBTs) and then expendable bathythermographs (XBTs) allowed much more frequent profiling of the upper ocean. MBTs recorded temperature versus depth on a smoked glass slide; XBTs telemetered data electrically as a probe fell through the water on a thin wire and was then
 270 detached (Oreskes, 2000). Merchant ships along regular routes could deploy these instruments, turning shipping



lanes into repeated sections of temperature profiles in the upper several hundred metres. Spilhaus (1938) described the bathythermograph and its early use, and later work quantified and corrected systematic depth and temperature biases in global MBT/XBT data (Gouretski and Reseghetti, 2010).

Between 1990 and 1998, the World Ocean Circulation Experiment (WOCE) coordinated global hydrographic surveys using high-precision conductivity–temperature–depth (CTD) instruments, providing detailed, though episodic, three-dimensional pictures of temperature and salinity. The Array for Real-Time Geostrophic Oceanography (ARGO) programme, designed to move measurements towards a continuous global monitoring system (Roemmich and Owens, 2000), began deploying floats in 1999 (Riser et al., 2016). Argo profiling floats were deployed across the world’s oceans; each float drifts at depth, then rises to the surface every ten days, measuring temperature and salinity as it ascends and transmitting the profile via satellite. By the late 2000s, the array had reached near-global coverage. Today’s estimates of ocean heat content, and thus of the imbalance between incoming and outgoing energy, rely heavily on the Argo network, supplemented by earlier MBT, XBT, CTD, and bottle data and by data-assimilation reanalyses (Abraham et al., 2013; Cheng et al., 2017; Durack et al., 2018).

An early global assessment of ocean warming came from the accumulated archives rather than from the new arrays. Heat content from the surface to 3,000 m, quantified for the period 1948 to 1998, showed a net warming of the world ocean: an increase of about 2×10^{23} J between the mid-1950s and the mid-1990s, equivalent to a volume-mean warming of 0.06 °C (Levitus et al., 2000). The result preceded near-global Argo coverage, on which the same quantity now depends, by seven years.

2.1.4 Earth’s heat inventory

The temperature records described above capture changes at specific locations and depths. A complementary perspective asks how much total energy the Earth system has accumulated. Figure 1d presents the Earth Heat Inventory, which partitions cumulative energy change across the ocean (at three depth layers), land, ice, and atmosphere.

The inventory approach was developed through coordinated multi-product assessments under the Global Climate Observing System (GCOS). Von von Schuckmann et al. (2020) and von von Schuckmann et al. (2023) assembled estimates from various ocean heat content products, satellite-derived ice-loss estimates, and land and atmospheric energy budgets to produce a total Earth heat budget extending from 1960 to 2020. The ocean dominates, absorbing approximately 89% of the total accumulated heat, with the 0–700 m top layer accounting for the largest share and the 700–2000 m layer contributing an increasing fraction in recent decades (von Schuckmann et al., 2023).

The inventory confirms what individual temperature records also show, but quantifies it in energy terms: Earth’s energy imbalance – the difference between absorbed solar radiation and outgoing longwave radiation – has roughly doubled between mid-2005 and mid-2019. Independent top-of-atmosphere radiation measurements from the Clouds and the Earth’s Radiant Energy System (CERES) satellites corroborate this acceleration (Loeb et al., 2021). The CERES measurements and the in situ inventory are interdependent by design (the CERES absolute calibration is



anchored to the in situ estimate) but track interannual variability independently, and their agreement strengthens
 305 confidence in the magnitude and trend of the imbalance.

Two features of the inventory merit emphasis. First, the pre-Argo era (before approximately 2005) carries sub-
 stantially larger uncertainties owing to sparse sampling of the deep and Southern oceans before Argo (Cheng et al.,
 2017). This is reflected in the wide uncertainty envelope in Fig. 1 before 2005. Second, the 1960 start date, adopted
 by the GCOS community, reflects the earliest period for which multi-decadal ocean warming trends can be reliably
 310 resolved; interannual variability cannot be confidently separated from sampling noise before this.

2.1.5 Section summary

Surface temperature has been recorded since the late seventeenth century (CET, 1659). It has standardised exposure
 and international coordination from 1873, a reconciled global mean in 1986 (Jones et al., 1986), and a reported trend
 in 1996 (Santer et al., 1996). Hansen et al. (1988) had forecast that the warming would become clearly identifiable
 315 in the 1990s, and said so in the Senate testimony in 1988. The identification itself came with the fingerprint analyses
 in 1996.

The upper air had a dedicated aerological observatory from 1898 (Hoinka, 1997), homogenised products from
 1958, detection in 1989 (Karoly, 1989), and reconciliation of the satellite with the radiosonde record in 2006 (U.S.
 Climate Change Science Program, 2006).

320 Ocean surface temperature has been measured with buckets since the 19th century and we have reconstructed a
 time series from 1850. However, measuring the heat of the ocean requires the measurement of temperature at depth.
 Expanding bathythermograph coverage made multi-decadal trends globally resolvable from 1960, the World Ocean
 Circulation Experiment surveyed the interior systematically from 1990, the trend was detected in 2000 (Levitus
 et al., 2000), and Argo brought the ocean interior under near-global observation in 2007.

325 In two of these three records the trend was detected before the observing system that would document it was
 complete. In the upper air the gap is seventeen years, from the detection of the vertical pattern in 1989 (Karoly,
 1989) to the reconciliation of the satellite and radiosonde records in 2006 (U.S. Climate Change Science Program,
 2006).

2.2 Cryosphere

330 Early observations of glaciers were the first robust empirical evidence suggesting that Earth's climate had once been
 radically different, and even today, “before” and “after” pictures of retreating glaciers are among the most cited
 visual evidence of global warming (Inkpen, 2018, 2022, 2023). However, the complex physics of the cryosphere has
 made it hard for scientists to quantify warming effects. Cryospheric records became systematic with the advent of
 satellite observations in the late twentieth century.

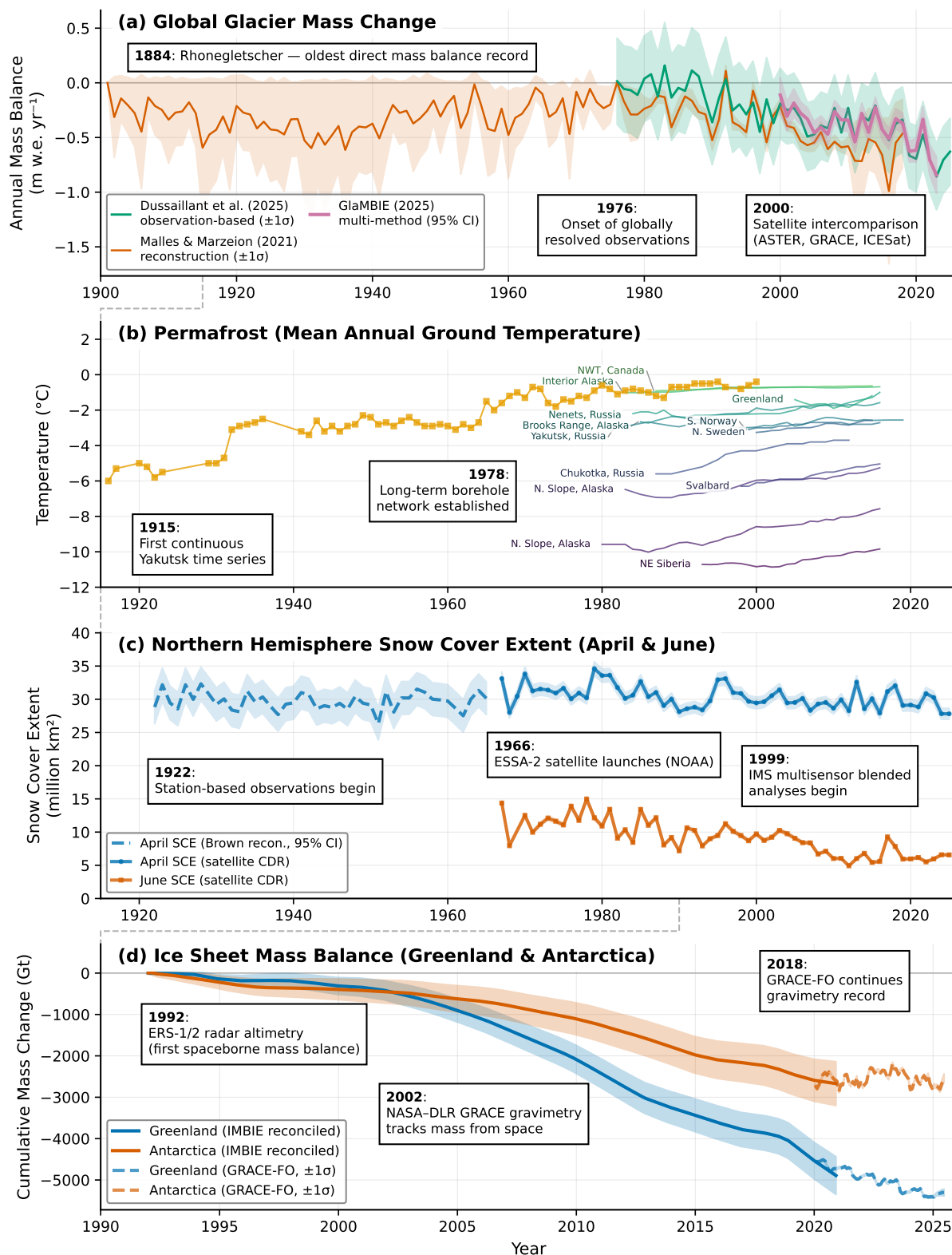




Figure 2. Decline in global cryosphere components. **(a)** Global glacier mass change (annual mass balance in metres of water equivalent per year, m w.e. yr^{-1}) showing the Malles and Marzeion (2021) reconstruction (1901–2018, 1σ scatter), observation-based estimates from the WGMS annual mass-change release of February 2026 (World Glacier Monitoring Service, 2026; 1976–2025, 1σ), produced by the method of Dussaillant et al. (2025), and GlaMBIE Team (2025) multi-method intercomparison (2000–2023, 95% confidence interval (CI)). Annotations mark the onset of globally resolved annual observations (1976) and the satellite intercomparison era (ASTER, GRACE, ICESat from ~ 2000). **(b)** Permafrost mean annual ground temperature showing Yakutsk 3.2 m depth July temperature (1916–2000) and thirteen individual borehole records selected from the Wiczorek et al. (2025) PANGAEA synthesis, at depths of 5 to 20 m and spanning Russia, Alaska, Canada, Svalbard, Greenland and Scandinavia, each plotted separately and labelled. **(c)** Northern Hemisphere snow cover extent in April and June, combining the Brown (2000) pre-satellite April reconstruction (1922–1965, 95% CI) with the Rutgers/NOAA satellite CDR (record from November 1966; the April and June series plotted begin in 1967, 3% uncertainty band). **(d)** Ice sheet mass balance for Greenland and Antarctica from IMBIE reconciled estimates (1992–2020, 1σ , solid lines) extended with NASA JPL GRACE/GRACE-FO mascons (2020–2025, dashed lines), offset to splice continuously to IMBIE at 2020.

335 2.2.1 Ice sheets

In Greenland, the ice sheet has long been well known to the Inuit communities living along its margins. Antarctica, by contrast, had no resident population and was effectively unknown until explorers reached its waters in the late eighteenth and nineteenth centuries. Quantitative information came first from coastal explorers and ship-based soundings in the nineteenth and early twentieth centuries, and then from aerial photography beginning in the late
 340 1920s and expanding through the 1930s. These efforts mapped the outlines of the ice sheets and some outlet glaciers but provided little information on mass balance (Barry and Gan, 2011). Thickness, as opposed to outline, was first measured on the German Greenland expeditions of 1929 to 1931. Alfred Wegener’s party used seismic sounding, timing the echo of a small explosion returning from the bed, to determine the depth of the inland ice at points along their traverse (Greene, 2018).

345 In the 1960s, airborne radio-echo sounding traced internal layers and bedrock topography, giving estimates of thickness and volume, while isolated stake networks and flux-gate calculations suggested that ice sheets might not be in perfect equilibrium (Mercer, 1967; Hughes, 1973). However, these data could not resolve decadal trends (Vaughan et al., 2013).

In the 1990s, satellite radar altimeters on ERS-1 and ERS-2 (launched in 1991 and 1995) provided the first
 350 continent-scale measurements of ice-sheet surface elevation change, albeit along sparse ground tracks (Wingham et al., 2006). Laser altimetry with ICESat (2003–2009) improved vertical precision, and CryoSat-2 (launched in 2010) introduced a synthetic-aperture radar altimeter optimised for ice margins, greatly increasing coverage in steep and coastal regions (Wingham et al., 2006).

Repeat airborne laser altimetry gave the first direct evidence of regional elevation loss in 1999. Surveys flown over
 355 southern Greenland in 1993 and 1994, and repeated over the same tracks in 1998 and 1999, showed thinning at the



margins that outweighed thickening in the interior, so that the surveyed region as a whole was inferred to be in negative balance (Krabill et al., 1999). The survey was extended to the whole ice sheet the following year, confirming the pattern of high-elevation balance with peripheral thinning (Krabill et al., 2000).

In 2002, the Gravity Recovery and Climate Experiment (GRACE) mission measured tiny changes in Earth’s gravity field, allowing direct estimates of mass loss from Greenland and Antarctica (Tapley et al., 2004; Velicogna, 2009). GRACE operated until 2017, and its successor GRACE Follow-On (GRACE-FO) (launched in 2018) has continued this near-continuous gravimetric monitoring of ice-sheet mass, apart from a roughly one-year gap between the two missions. Satellite interferometry and feature tracking added velocity fields, enabling “input–output” calculations of mass budgets based on surface mass balance and ice discharge (Vaughan et al., 2013).

In 2012, the Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE) reconciled these different satellite methods. Shepherd et al. (2012) combined altimetry, gravimetry and input–output estimates into a single, time-consistent mass-balance record and showed that the three techniques agreed within uncertainties. Subsequent IMBIE assessments extended these reconciled records, most notably for Antarctica (IMBIE Team, 2018) and, more recently, for both ice sheets from 1992 to 2020 (Otosaka et al., 2023). GRACE-FO gravimetry now extends the mass-change record through approximately mid-2025 with roughly monthly updates from all three processing centres (JPL, CSR, and GFZ). Figure 2 uses the GRACE-FO time series to extend the Greenland and Antarctica records beyond the IMBIE endpoint, with the change in uncertainty bands reflecting the transition from multi-technique reconciliation to single-technique monitoring. The reconciled IMBIE record places cumulative ice mass losses over 1992–2020 at 4,892 ± 457 Gt for Greenland and 2,671 ± 530 Gt for Antarctica, corresponding to roughly 14 mm and 7 mm of global mean sea-level rise respectively (Otosaka et al., 2023) (described in more detail in the sea-level rise section). The combined rate of ice-sheet mass loss rose from approximately 105 Gt/yr in the early 1990s to approximately 372 Gt/yr by 2016–2020, a roughly 3.5-fold acceleration (Otosaka et al., 2023).

Figure presents Greenland and Antarctica as separate traces, following the convention adopted by IPCC AR6 (IPCC, 2021) and the IMBIE papers (IMBIE Team, 2018). Separation is scientifically warranted because the ice sheets differ in their onset timing, dominant physical drivers, and internal variability structure. Greenland has lost mass consistently since the mid-1990s, with losses split roughly evenly between surface melting driven by atmospheric warming and increased dynamic discharge. Antarctica’s losses are dominated by ocean-forced thinning of ice shelves in West Antarctica, with East Antarctica near balance but subject to large snowfall-driven variability, producing a different temporal signature in which the loss trend is partly masked by interannual noise (IMBIE Team, 2018; Boening et al., 2012).

From a data-quality viewpoint, ice-sheet mass balance became consistent in the early 1990s, when continuous satellite altimetry began, and fully so with the combination of altimetry, gravimetry and velocity fields into reconciled estimates after about 2002.



2.2.2 Glaciers

390 By the early nineteenth century, the retreat of Alpine glaciers from Little Ice Age maxima (1400-1800) had been documented in paintings, maps, and field surveys; observations of erratic boulders and moraines provided key evidence for Louis Agassiz's proposal that extensive continental glaciation had once occurred (Barry and Gan, 2011). Systematic monitoring developed through the late nineteenth century.

In 1827 Franz Joseph Hugi built a hut on the Unteraar glacier in the Bernese Alps and marked a large boulder
 395 beside it; by 1836 the boulder had travelled 1,315 m down-glacier. Clarke (1987) judges these to be the first actual measurements of glacier flow. Repeated position measurements of this kind, and the front-variation surveys that followed them, are the origin of the instrumental glacier record.

In 1894, the International Glacier Commission was established and began collecting front-variation observations, later extended to mass-balance measurements, a function now carried out by the World Glacier Monitoring Service
 400 (WGMS) through its Fluctuations of Glaciers (FoG) database, which maintains standardised glaciological mass balance records from approximately 500 glaciers worldwide.

Whether the retreat was a global signal rather than an accumulation of regional ones was tested quantitatively in 1994. Analysing a worldwide compilation of glacier length records, Oerlemans (1994) found the retreat of the preceding century to be coherent across the globe and consistent with a linear warming trend of about 0.66°C
 405 per century. The glaciers had been described as retreating for well over a century by then; what was new was the demonstration that they were retreating together.

In 2010–2012, the Randolph Glacier Inventory (RGI), the first globally complete catalogue of glacier outlines, was compiled specifically to enable the IPCC AR5 assessment; the version used there covered some 198,000 glaciers and approximately 727,000 km² (Pfeffer et al., 2014). Successive versions, most recently RGI 7.0 with some 274,000
 410 glaciers, serve as the spatial framework for all modern global assessments (RGI Consortium, 2023).

From about 2000, satellite imagery transformed the picture of global glacier change. Stereo digital elevation models from ASTER and later sensors enabled geodetic mass change estimates for previously unmonitored glaciers. In 2002, the launch of GRACE added gravimetric basin-scale measurements, and ICESat (2003–2009) and ICESat-2 (2018 onward) contributed laser altimetry for individual glacier elevation change. However, constructing a globally
 415 representative glacier mass change record proved far more difficult than assembling a temperature series or a tide-gauge network (described in more detail in the Tide Gauge section), because in situ mass-balance measurements existed for only a small and unrepresentative sample of glaciers – concentrated in the European Alps, Scandinavia, and a few accessible North American sites – whereas the regions that hold most of the world's glacier ice, including Arctic Canada, Alaska, the Russian Arctic, and High Mountain Asia, had little or no ground-based monitoring
 420 (Pfeffer et al., 2014). Satellite geodesy resolved this gap, ultimately yielding elevation-change estimates for essentially every glacier on Earth (Hugonnet et al., 2021).



Three approaches now provide overlapping, methodologically independent reconstructions of global glacier mass change. The climate-forced model reconstruction (Malles and Marzeion, 2021), shown in Fig. 2a, uses a temperature-index mass balance model driven by nine different meteorological forcing datasets to reconstruct global glacier mass change from 1901 to 2018. This provides a long temporal perspective but depends on the quality of historical climate reanalyses. Dussaillant et al. (2025), building on the landmark Zemp et al. (2019) assessment, fused geodetic satellite observations (now covering approximately 96% of the world's glaciers) with in situ glaciological measurements to produce an observation-based record from 1976 to 2024. The GlaMBIE community intercomparison (GlaMBIE Team, 2025) reconciled 233 regional estimates from approximately 450 contributors, combining all four major observation methods (glaciological, geodetic, altimetric, and gravimetric) into the most precise modern assessment, covering 2000–2023 with cumulative losses of 6,542 387 Gt (approximately 18 mm sea-level equivalent) and a 36 10% acceleration from the first to the second half of the study period.

Figure 2 shows that these three approaches, built on fundamentally different data and methods, converge on the same accelerating trend of global glacier loss. Their estimates, expressed as sea-level equivalent (SLE) – the global sea-level rise produced by a given loss of ice – are 0.92 mm SLE/yr for 2006–2016 (Zemp et al., 2019), 0.90 mm SLE/yr for 2006–2018 (Malles and Marzeion, 2021), and 0.75 mm SLE/yr averaged over the longer 2000–2023 window, with higher rates towards its end (GlaMBIE Team, 2025).

2.2.3 Snow cover

Historically, snow cover was among the easier cryospheric variables to observe, as it was measured at weather and hydrological stations where snow depth and water equivalent were recorded for forecasting floods and water supply. These records are long but spatially sparse and strongly biased towards populated regions (Barry and Gan, 2011).

In 1966, NOAA began weekly mapping of snow cover across the Northern Hemisphere, using images from the ESSA meteorological satellites (Robinson et al., 1993). Analysts visually interpreted the images and drew snow/no-snow boundaries by hand onto charts, which were then digitised. These charts created the first multi-decadal, hemispheric-scale snow-cover record. Robinson et al. (1993) reviewed this programme and proposed methods to homogenise the record.

In June 1999, NOAA replaced the weekly charts with daily maps from the Interactive Multisensor Snow and Ice Mapping System (IMS), which blends visible, infrared and microwave satellite imagery with in situ data (Helfrich et al., 2007). The resulting Snow Cover Extent Climate Data Record (SCE CDR) reprocesses the full 1966–present record into a single, quality-controlled Northern Hemisphere time series: the early weekly charts were revised at Rutgers University, and the later daily IMS output converted to a consistent weekly basis and reconciled across a two-year overlap (Robinson et al., 1993, 2012; Estilow et al., 2015).

Ground-station networks across Canada, the United States, the former Soviet Union, and China had recorded daily snowfall, maximum temperature, and snow depth since the late nineteenth century, and from 1922 their combined coverage is dense enough to support a hemispheric estimate. Brown (2000) reconstructed Northern Hemisphere



spring snow-cover extent from these observations using an areal snow-cover index derived from station snow-depth data. The index was calibrated and validated against the overlapping satellite-era record before being applied to the earlier station data. Archived at NSIDC as G02131, the reconstruction supplies the pre-1966 portion of Fig. 2, with the satellite CDR covering 1966 to present. The two were first merged into a single homogeneous series in 2011
 460 (Brown and Robinson, 2011), and the merge was later extended using standardised anomalies into a continuous century-long record (Mudryk et al., 2020), which shows no earlier episode of sustained spring snow-cover decline comparable to that of recent decades. The decline itself was reported as statistically significant well before those merged datasets existed. Comparing the first two decades of the satellite record showed the reduction in Northern Hemisphere snow cover to be significant at the 0.01 level (Robinson and Dewey, 1990), and the result was placed on a
 465 century-long footing by the reconstruction described above, which shows the recent decline to be without precedent since 1915 (Brown, 2000).

The figure shows both April and June snow-cover extent. June trends are roughly ten times steeper than April's in percentage terms (about 13% versus 1.4% per decade, respectively), reflecting the amplified snowmelt response in late spring. The two are complementary: April's larger extent (28–30 million km², mid-latitudes to Arctic) carries
 470 the broader geographic signal and the longer reconstructed record, while June's smaller, high-latitude extent (5–10 million km²) tracks the most rapidly changing part of the seasonal cycle.

2.2.4 Permafrost

Well before the twentieth century, frozen ground was central to life in high-latitude regions; Russian engineers and Indigenous communities developed practical knowledge of *вечная мерзлота* (*vechnaya merzlota* (translit.), or
 475 “eternal frost”) well before it was framed as a climate indicator.

In the early twentieth century, quantitative permafrost monitoring began with ground-temperature measurements near settlements such as Yakutsk, where the archived series of shallow ground temperatures begins in 1916 (Zhang, 2011). Later, Soviet and North American researchers drilled deep boreholes to track mean annual ground temperature at the depth of zero annual amplitude. However, methods and metadata varied between programmes.

480 Even before those programmes were harmonised, the boreholes themselves carried a usable climate record. Heat moves through cold permafrost by conduction alone, so a temperature profile measured on a single visit preserves the imprint of past surface temperature change, and that imprint can be recovered by inverting the profile. This reasoning was applied to profiles from northernmost Alaska, where the upper 100 m showed anomalous curvature, and yielded an inferred widespread warming of the permafrost surface of 2 to 4°C over the preceding few decades
 485 to a century (Lachenbruch and Marshall, 1986). Comparable warming was later reported from the Russian Arctic, where Pavlov (1994) found ground temperatures at 3 m depth in the European north-east rising by 0.6 to 0.7°C between 1970 and 1990, and along an Alaskan transect, where repeat measurements tracked 0.5 to 1.5°C of warming at the permafrost table together with the onset of thawing (Osterkamp and Romanovsky, 1999). Both of those studies attributed much of the recent warming to deepening snow cover rather than to rising air temperature, a



490 reminder that the ground-thermal signal integrates more than one forcing. The permafrost signal was therefore legible decades before the monitoring network was standardised, because the medium itself stored a history that the observing system had not yet had time to accumulate.

From the early 1980s, efforts to standardise permafrost monitoring intensified. Borehole networks in Alaska, Canada, Russia and Nordic countries adopted common protocols for sensor placement and logging intervals, and, 495 from its founding in 1983, the International Permafrost Association promoted coordination. Romanovsky et al. (2010) summarised the “Thermal State of Permafrost” project for the International Polar Year, showing widespread warming in boreholes across the Northern Hemisphere over the preceding decades.

In the late 1990s, the Global Terrestrial Network for Permafrost (GTN-P) formalised permafrost observation into an international observing system. The Network maintains databases for borehole temperatures and active-layer 500 thickness, with standard metadata and open access (Biskaborn et al., 2015; Clow, 2014).

Using GTN-P data, Biskaborn et al. (2019) compiled the first globally consistent assessment of permafrost temperature change, showing a mean warming of about 0.3°C between 2007 and 2016 across permafrost regions. Figure 2 illustrates this maturation by setting the single Yakutsk station record beside thirteen borehole records selected from the Wiczorek et al. (2025) synthesis, which extends the archive four years beyond the Biskaborn et al. (2019) 505 assessment endpoint of 2016. The thirteen are plotted individually rather than combined, at depths between 5 and 20 m and across Russia, Alaska, Canada, Svalbard, Greenland and Scandinavia, so the spread between sites and the difference between shallow and deep sensors both remain visible; almost every record rises over its period of overlap, strongest where permafrost is coldest.

2.2.5 Section summary

510 In 1968 Mercer argued from glacial-geological evidence that the West Antarctic Ice Sheet had been smaller in the past and was inherently vulnerable because it is grounded below sea level (Mercer, 1968), and in 1978 he warned that anthropogenic carbon dioxide (CO₂) warming could trigger its deglaciation and a multi-metre sea-level rise (Mercer, 1978); both claims remain unresolved (Lau et al., 2023; IPCC, 2021). IMBIE documented a roughly three-fold rise in West Antarctic losses over the satellite era in 2018 (IMBIE Team, 2018).

515 Measured against the four thresholds of Fig. 5, this family is the least synchronous of the four. Glaciers were measured first and reconciled last: Hugi’s marked boulder in 1827, the International Glacier Commission in 1894, a coherent global signal identified in 1994 (Oerlemans, 1994), and a reconciled global record only in 2025 (GlaMBIE Team, 2025), a span of almost two centuries. Ice sheets run the other way, from the first aerial mapping and thickness soundings at the end of the 1920s, through standardised satellite altimetry from 1992, to reconciliation in 520 2012 (Shepherd et al., 2012), with the first measured mass loss in between (Krabill et al., 1999). Snow cover crossed all four thresholds in just over seventy years: station coverage sufficient for a hemispheric estimate from 1922, satellite mapping from 1966, a significant hemispheric decline reported in 1990 (Robinson and Dewey, 1990), and a homogenised record in 1993 (Robinson et al., 1993). Permafrost is the extreme case in the other direction: ground



temperatures at Yakutsk from 1916, a coordinated network in 1999, and a global synthesis in 2019 (Biskaborn et al.,
 2019), yet the warming had been read from the curvature of Alaskan borehole profiles as early as 1986 (Lachenbruch
 and Marshall, 1986), thirty-three years earlier. In all four records the change was detected before the record that
 would eventually document it was complete.

2.3 Sea-level rise (SLR)

Sea level integrates several aspects of the climate system. Changes in sea level are a function of both complicated
 vertical land motion at particular coasts and increases in sea water volume and density (due to salinity) from
 climate change: thermal expansion of seawater and the loss of land ice raise the height of the ocean surface. Accurate
 understanding therefore requires measurements of both.

2.3.1 Tide gauges

From the late eighteenth century, local tide gauges were installed for navigation, harbour management, and geodesy,
 producing the first instrumental records of sea level, overwhelmingly in Europe. A handful of series reach back to the
 18th century: Liverpool (UK) to 1768, Stockholm (Sweden) to 1774, and Kronstadt (Russia) to 1777 (Woodworth,
 1999; Ekman, 1988). Stockholm is the world's longest continued series of annual mean sea levels (Ekman, 1988), while
 Brest (France) where datum-checked measurements extend back to 1807 and is the canonical reference for long-term
 change (Wöppelmann et al., 2008, 2006). The instrument then spread with industrial and colonial infrastructure:
 the U.S. Coast Survey introduced self-recording gauges in the mid-nineteenth century, including in San Francisco
 (1854), creating one of the longest Pacific series and pioneering automated monitoring. Comparable records appeared
 in Asia and the Southern Hemisphere later, in the late nineteenth and early twentieth centuries, and typically through
 the infrastructure of treaty ports and colonial administration rather than independent national geodesy. Tide-gauge
 measurements were made in Hong Kong's Victoria Harbour in 1887–1889 by William Doberck, the first director of
 the Hong Kong Observatory, and became the basis for local tide predictions from 1893 (Mok and Lui, 2016); China's
 longest continuous series, at Wusong (Shanghai), begins in 1912, when the Shanghai Waterway Bureau installed a
 gauge on the Huangpu River near an earlier station dating from the opening of the Wusong Customs in 1860 (Hu
 et al., 2026).

In 1933, at the Lisbon assembly of the International Union of Geodesy and Geophysics, the International Association
 of Physical Oceanography established a Committee on Mean Sea Level and its Variations, tasked with assembling
 monthly and annual means from tide gauges worldwide, along with metadata on station locations, benchmarks, and
 datums. The committee was renamed the Permanent Service for Mean Sea Level (PSMSL) after the International
 Geophysical Year and became a Permanent Service of the International Council of Scientific Unions in 1958; it is
 operated in the UK at what is now the National Oceanography Centre. This step is analogous to the institutional-
 isation and homogenisation of land-based temperature observations: it did not solve all problems, but it established
 the coordinated infrastructure on which subsequent reconstructions have depended.

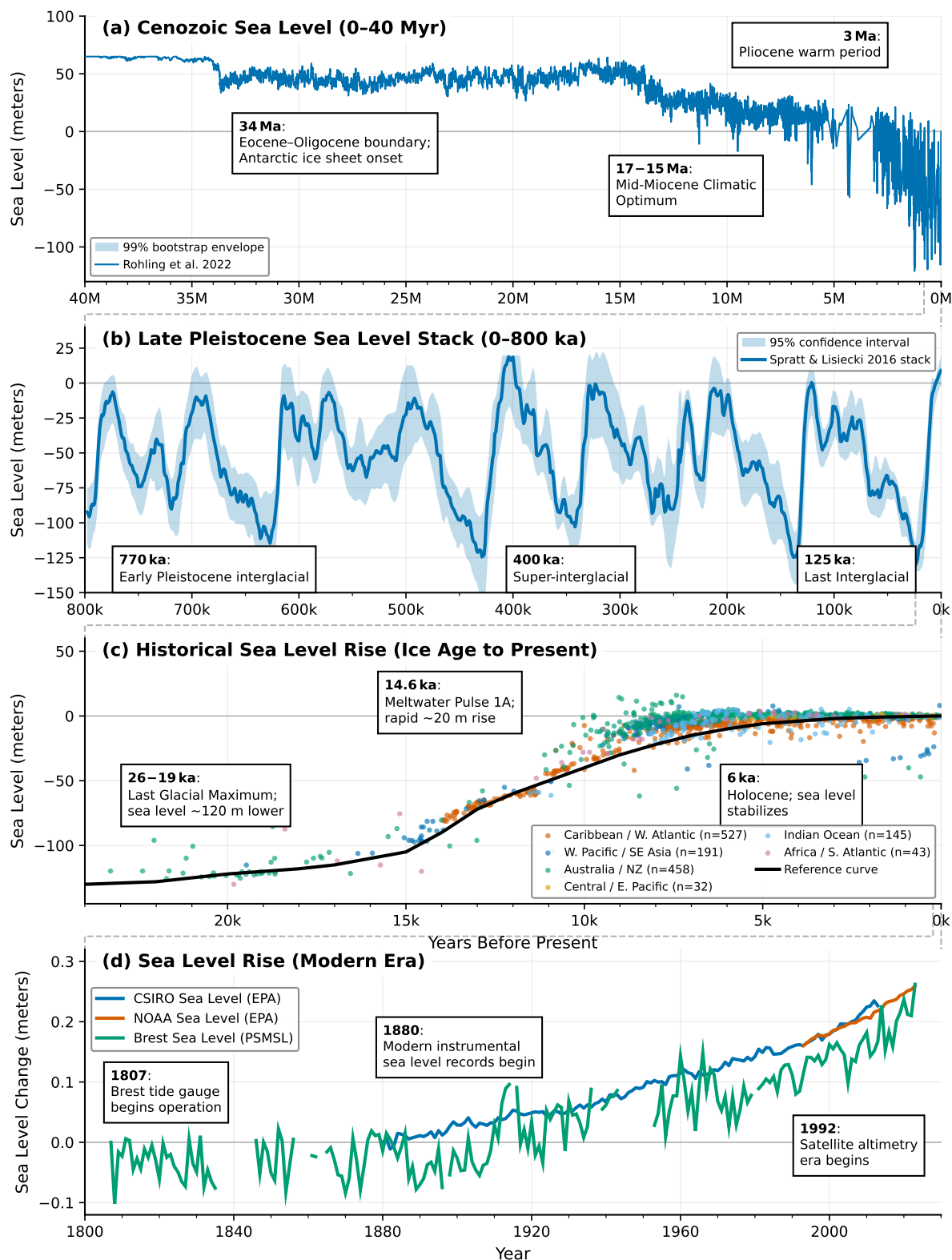




Figure 3. Sea level change across four nested timescales, from the Cenozoic to the modern era. Panels are arranged top-to-bottom from longest paleoclimate timescale to most recent, forming a continuous zoom sequence; dashed connectors between panels mark the sub-range of the panel above that the next panel expands. **(a)** Cenozoic sea level over the past 40 Myr from Rohling et al. (2022); bootstrap median with 99% confidence envelope shaded), with annotations marking the Eocene–Oligocene boundary and onset of the Antarctic ice sheet (~ 34 Ma), the Mid-Miocene Climatic Optimum (~ 17 – 15 Ma), and the Pliocene warm period (~ 3 Ma). **(b)** Spratt and Lisiecki (2016) Late Pleistocene principal-component sea-level stack (0–800 ka, 5-record long PC1 with 95% confidence band), with the three highest-stand interglacials labelled by age (770 ka Early Pleistocene interglacial, 400 ka super-interglacial, 125 ka Last Interglacial / Eemian). **(c)** Post-glacial sea-level markers from Hibbert et al. (2018); $\sim 1,400$ individually dated geological and biological indicators after quality filtering, plotted as a scatter coloured by region – Caribbean / W. Atlantic, W. Pacific / SE Asia, Australia / NZ, Central / E. Pacific, Indian Ocean, Africa / S. Atlantic) with a separate reconstructed sea-level curve overlaid in black for reference; annotations mark the Last Glacial Maximum (~ 26 – 19 ka, sea level ~ 120 m below present), Meltwater Pulse 1A (~ 14.6 ka, rapid ~ 20 m rise), and Holocene sea-level stabilisation (~ 6 ka). **(d)** Recent sea level change (1800–2023) showing the EPA-compiled CSIRO and NOAA reconstructions (converted from inches to metres) together with the Brest tide-gauge record (PSMSL, normalised to its first observation). Annotations mark the start of the Brest record (1807), the start of the global tide-gauge network (1880), and the start of the satellite altimetry era (1992).

Interpreting tide-gauge records as indicators of global mean sea level required separating changes in ocean volume from changes in the height of the land itself. Globally synchronous changes in ocean volume are termed “eustatic”, and changes in the position of the land are termed “isostatic”. In the global average, the dominant and most spatially coherent component of vertical land motion is glacial-isostatic adjustment (GIA) – the ongoing viscoelastic response of the solid Earth to the removal of Pleistocene ice – which is why reconstructions apply GIA models when combining gauges. At individual sites, however, the land surface can be governed by other processes: tectonic uplift or subsidence (for example along subduction zones), human-induced subsidence from groundwater and hydrocarbon extraction, and the compaction of unconsolidated sediment. In subsiding deltaic and coastal-plain settings (e.g. the Mississippi Delta of southern Louisiana being a well-documented case, with present-day relative sea-level rise in the order of 10 mm/yr, several times the global mean) such local land motion can exceed the rate of climate-driven sea-level rise. At individual gauges it can dominate the record entirely: at Galveston Pier 21, Texas, aquifer-system compaction driven by groundwater extraction has been estimated to account for as much as $\sim 85\%$ of the ~ 0.7 m of relative sea-level rise observed since 1909 (Liu et al., 2020). Because coastal populations are preferentially located in such subsiding lowlands, the relative sea-level rise they experience is on average faster than the global mean (Nicholls et al., 2021). Separating the eustatic signal therefore requires per-station information on vertical land motion, not a GIA correction alone.

Modern reconstructions correct for glacial-isostatic adjustment (GIA) using viscoelastic Earth models and, where possible, incorporate geodetic estimates of vertical land motion from the Global Positioning System (GPS) to adjust individual tide-gauge series before combining them into a global curve (Mitrovica and Milne, 2003; Peltier, 2004;



Wöppelmann and Marcos, 2016; Dangendorf et al., 2017). As with early thermometer networks, careful attention to station history, benchmark stability and sampling biases is essential to extract a robust global signal from uneven, coastally distributed observations.

Whether the gauges showed a global rise, rather than the sum of local land motions, was answered quantitatively in 1982. Combining the available records with an explicit treatment of their geographic distribution gave a rise of about 12 cm over the preceding century, highly correlated with the trend in global surface air temperature (Gornitz et al., 1982). Douglas (1991) refined the estimate to 1.8 ± 0.1 mm per year over 1880 to 1980 using a smaller set of gauges selected for tectonic stability and record length. Both results precede the satellite altimeters by a decade.

2.3.2 Satellite altimetry and the sea-level budget

The 1992 launch of a joint NASA–CNES satellite carrying a radar altimeter (TOPEX) and an experimental French altimeter (Poseidon) marked a transition from coastal records to a global sea-level indicator. TOPEX/Poseidon was the first mission to provide precise, near-global measurements of sea-surface height relative to an Earth-centred reference frame. Its successors, the so-called Jason series, have extended this record, delivering maps of sea level every 10 days over most of the ice-free ocean (Cazenave and Nerem, 2004). These altimetric estimates show a clear rise in global mean sea level (GMSL) since the early 1990s and a statistically significant acceleration within the altimeter era itself (Nerem et al., 2018); tide-gauge reconstructions place the onset of persistent acceleration in the 1960s (Dangendorf et al., 2019).

From the early 2000s, understanding the causes of this rise required complementary observations of ocean temperature, salinity and land-ice mass. The Argo profiling-float programme provided global, repeated profiles of temperature and salinity to 2000 m depth, allowing direct estimates of the steric (thermal-expansion and haline, i.e. salinity) contribution to sea-level change (Riser et al., 2016; Jayne et al., 2017). In 2002, satellite gravimetry from GRACE (and later GRACE-FO) began to quantify mass loss from glaciers and ice sheets and changes in terrestrial water storage, completing the observational toolkit needed to close the sea-level budget.

The “sea-level budget” approach sums these contributions and compares the total to the directly observed GMSL from altimetry. Steric expansion and land-ice mass loss together explain most of the observed rise and its acceleration, and the budget closes to within reported uncertainties (WCRP Global Sea Level Budget Group, 2018).

2.3.3 Reconstructions of past sea level

Tide gauges and satellites document roughly the last 150–200 years of sea level change; to place this into a longer context, researchers use geological and geochemical indicators of past sea level. In the nineteenth century, glacial theory established that large ice sheets once covered much of the Northern Hemisphere, implying large global sea-level differences between glacial and interglacial periods.

In the mid-twentieth century, oxygen-isotope stratigraphy tied variations in deep-ocean $\delta^{18}\text{O}$ to changes in global ice volume and deep-water temperature (Emiliani, 1955). Far-field coral terraces, dated by radiocarbon and later



by U–Th methods and corrected for local vertical land motion, provided absolute benchmarks and have shown, for
 610 example, that sea level at the Last Glacial Maximum (LGM, between 26,000 and 20,000 years ago) was about 120
 m lower than today (Fairbanks, 1989). More recent work combines such records with GIA modelling to reconstruct
 global mean sea level through the last deglaciation and the Holocene (Lambeck et al., 2014). Over the last two
 millennia, salt-marsh and other coastal proxy records have been assembled into spatially resolved reconstructions
 that reveal regional differences and highlight the gradual sea level rise in the late nineteenth and twentieth centuries
 615 (Kemp et al., 2011; Hay et al., 2015; Kopp et al., 2016), a pattern of millennial stability broken by accelerating rise
 since the mid-nineteenth century recently confirmed for the western Pacific margin (Lin et al., 2025).

These palaeo-records perform a role analogous to that of ice cores in the greenhouse-gas section: they extend the
 instrumental record, show the range of natural variability, and link sea level to past changes in climate and ice sheets.

2.3.4 Process understanding and projections

620 In the 1970s, theoretical and numerical work on grounding-line dynamics showed that marine-based ice sheets
 grounded below sea level could be inherently unstable, a phenomenon known as marine ice-sheet instability (Weert-
 man, 1974; Thomas and Bentley, 1978; Hughes, 1973). Mercer (1978) warned that CO₂-driven warming could
 deglaciate West Antarctica and produce a rapid five-metre rise in sea level.

Subsequent modelling and observations refined this picture. Grounding-line theory was placed on firmer mathe-
 625 matical footing (Schoof, 2007), and the hypothesis of marine ice-cliff instability was advanced to explain potentially
 very rapid retreat where tall ice cliffs become exposed after ice-shelf collapse (Pollard et al., 2015; DeConto and
 Pollard, 2016). Its importance for twenty-first-century sea level remains contested: subsequent modelling showed
 that ice-cliff instability is not required to reproduce past sea-level change (Edwards et al., 2019), and the IPCC
 Sixth Assessment Report accordingly treated marine ice-cliff instability as a process of low confidence and deep
 630 uncertainty rather than an established control on its central projections (Fox-Kemper et al., 2021). More recent
 work using three independent ice-sheet models suggests the West Antarctic Ice Sheet is unlikely to be vulnerable to
 marine ice-cliff instability during the present century (Morlighem et al., 2024). Satellite gravimetry and altimetry
 revealed accelerating mass loss from Greenland and Antarctica in the early 21st century; reconciled estimates from
 IMBIE and related efforts are now central to constraining ice-sheet contributions to past and future sea-level change
 635 (Shepherd et al., 2012; IMBIE Team, 2018; Otosaka et al., 2023). Structured expert-judgement studies complement
 process-based models by characterising deep uncertainty in high-end sea-level outcomes (Bamber et al., 2019).

Assessments by the IPCC synthesise this evolving evidence. The IPCC’s first assessment in 1990 reports provided
 broad ranges for projected global mean sea-level rise based on relatively simple models. More recent assessments
 combine process-based projections, semi-empirical approaches and expert judgement, and present probabilistic ranges
 640 that explicitly reflect uncertainty in ice-sheet dynamics as well as greenhouse-gas emissions. The IPCC projections
 of future sea-level rise have been much debated (e.g. Rahmstorf, 2007; Garner et al., 2018), a debate that has since
 been reframed around the deep uncertainty in ice-sheet dynamics. AR6 reports likely ranges reaching ~1 m by 2100



under high emissions, alongside an explicit low-confidence high-end storyline in which rise approaching 2 m by 2100 (and 5 m by 2150) cannot be ruled out (Fox-Kemper et al., 2021). For the purposes of this review, the key point is that these projections rest on the observational backbone formed by tide gauges, satellite altimetry, ocean profiles and land-ice mass-balance records.

2.3.5 Section summary

Local sea-level change has been recorded since the late eighteenth century, and Anders Celsius had already recognised that apparent change at any one coast reflects vertical land motion as well as ocean volume. Institutionalisation came with the Permanent Service for Mean Sea Level in 1933, and bias-corrected reconstructions reaching back to the late nineteenth century, with explicit glacial-isostatic and vertical-land-motion corrections, emerged in the 2000s. Two further steps were needed. Near-global satellite altimetry from TOPEX/Poseidon removed the coastal sampling bias of the gauges and revealed a statistically significant acceleration (Nerem et al., 2018), corroborated over the longer tide-gauge record (Dangendorf et al., 2019); and closure of the sea-level budget partitioned the rise among its physical drivers (WCRP Global Sea Level Budget Group, 2018), a budget AR6 assesses as consistent over 1901 to 2018 with the sum of its components.

Completeness here refers to detecting and attributing past and present change, not to projecting it. The future ice-sheet contribution, through atmospheric warming-driven ice-shelf disintegration and the possible onset of marine ice-sheet and contested marine ice-cliff instabilities in Antarctica, remains uncertain enough that AR6 excludes these processes from its assessed likely ranges and treats them through a low-likelihood, high-impact storyline in which global mean sea level approaching 2 m by 2100 cannot be ruled out (DeConto and Pollard, 2016; Edwards et al., 2021; IPCC, 2021).

On the thresholds of Fig. 5, sea level is a single indicator carried by two successive observing systems, and each milestone is taken from whichever system reached it first. The tide gauges supply the first systematic record (Liverpool, 1768) and the standardised network (PSMSL, 1933); satellite altimetry supplies the globally robust one (TOPEX/Poseidon, 1992). Detection sits between them and belongs to the gauges: the rise was identified as global, and tied to surface temperature, in 1982 (Gornitz et al., 1982). The 2018 acceleration result (Nerem et al., 2018) is a later and different claim, namely that the rate itself is increasing, and it should not be read as the date at which the rise was first detected.

2.4 Greenhouse Gases

Long-lived greenhouse gases – carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and a suite of synthetic gases – link radiative physics to human activities. Today we can combine three kinds of evidence: high-precision in situ measurements from background stations and global networks; ocean time-series that track the uptake of CO_2 that changes pH; and reconstructions of past atmospheric composition from air trapped in polar ice over hundreds of thousands of years (Etheridge et al., 1996; Lüthi et al., 2008; World Meteorological Organization, 2024).



2.4.1 From heat experiments to the idea of greenhouse gases

In the 1820s, Fourier argued that Earth’s temperature is controlled by the balance between incoming solar radiation and outgoing heat, and that the atmosphere modifies this balance by partially trapping heat (Fourier, 1827; Fleming, 1999; Weart, 2008). In 1856, Eunice Newton Foote reported that a glass cylinder of carbonic acid gas warmed more
 680 in sunlight, and cooled more slowly afterwards, than one of ordinary air, and suggested that a higher proportion of that gas would give the Earth a higher temperature (Foote, 1856). Her apparatus used visible sunlight rather than infrared radiation, so it did not isolate the mechanism, and there is no evidence that the work was known to those who followed (Jackson, 2020). Five years later, Tyndall built an apparatus to test the hypothesis directly: a beam of infrared radiation passed through tubes filled with different gases. He found that water vapour, CO₂ and other trace
 685 gases absorbed heat strongly, whereas dry air did not (Tyndall, 1861). In 1896, Arrhenius used available absorption data and a simple energy-balance model to calculate how doubling atmospheric “carbonic acid” would change global temperature, effectively producing the first quantitative climate-sensitivity estimate (Arrhenius, 1896).

In 1900, Knut Ångström reported laboratory measurements which he read as showing that CO₂ absorption was already saturated at atmospheric concentrations, so that adding more could have little further effect (Ångström,
 690 1900). The objection was influential for a generation, and it is why the theoretical line in Fig. 5 is drawn as unsettled until the late 1930s. In 1938, Callendar revisited the question, compiling early CO₂ measurements together with land-station temperature records, from which his series was later reconstructed using 147 stations (Hawkins and Jones, 2013). He argued that fossil-fuel combustion was already raising atmospheric CO₂ and contributing to the observed warming (Callendar, 1938). His temperature record was not global: drawn from land stations spanning roughly
 695 60°S to 60°N, it had little coverage of the oceans or the polar regions, though it did include both hemispheres and the tropics. Nevertheless, a modern comparison of his published series against present-day reconstructions finds his estimated land-temperature trend was close to modern values (Hawkins and Jones, 2013). What his data could not yet do was demonstrate, from observations alone, that the warming was attributable to CO₂; that step required the global instrumental record and detection-attribution analyses that came decades later.

700 In 1957, Revelle and Suess combined simple carbon-cycle calculations with ocean chemistry, showing that the buffer chemistry of seawater limits how much added CO₂ the ocean can take up, so that a substantial fraction of emissions must remain in the atmosphere (Revelle and Suess, 1957). Therefore, by the mid-twentieth century, the conceptual link between CO₂, radiative forcing, and human emissions was in place.

Establishing causation, however, required comparing the observational record to physically based models, which
 705 could analyse the contributions of different forcings. Hansen et al. (1981) used a one-dimensional radiative-convective model with a simple ocean to simulate the observed 1880-1980 temperature record. They found the warming of about 0.4°C over the past century was consistent with the measured CO₂ increase, and that volcanic aerosols could account for much of the fluctuation around the trend. On that basis they predicted that the CO₂ warming “should emerge from the noise level of natural climate variability by the end of the century”. Hansen et al. (1988) extended the



exercise to a three-dimensional general circulation model run forward from 1958 under three emission scenarios, and included the effects of volcanic aerosols; they concluded that greenhouse warming was underway, and “should be clearly identifiable in the 1990s”. Testifying to the U.S. Senate on 23 June 1988, Hansen stated with 99 per cent confidence that the warming trend was real, and ascribed a cause-and-effect relationship to the greenhouse effect “with a high degree of confidence” – a public judgement that ran somewhat ahead of the formal statistical attribution then available.

As Hansen and his colleagues recognized, attribution in the formal sense had to reckon with aerosols. Sulphate aerosols, which have a cooling effect, are produced both by volcanic eruptions and by air pollution. The latter is the largest anthropogenic forcing apart from greenhouse gases; aerosols have been called “the source of our greatest uncertainty about climate forcing” (Hansen and Lacis, 1990). When transient coupled ocean-atmosphere simulations first incorporated the sulphate effect, adding that cooling to greenhouse-gas forcing “significantly improve[d] the agreement with observed global mean and large-scale patterns of temperature in recent decades”, and helped to explain why the observed warming, particularly in the mid-20th century, was less than greenhouse-gas-only model runs implied it should be (Mitchell et al., 1995). The pattern-based fingerprint work behind the IPCC’s 1995 “discernible human influence” conclusion rested on this combination of greenhouse-gas and aerosol signals (Santer et al., 1996). Natural forcings and internal variability alone could not reproduce the observed post-war warming, which was recovered only in simulations that included the combined greenhouse-gas and sulphate-aerosol signal (Tett et al., 1999; Stott et al., 2000). All of this, however, lay decades ahead: what was missing at mid-century was a measurement system that could track atmospheric composition precisely over time.

2.4.2 Direct atmospheric CO₂: from chemical assays to the Keeling Curve

Before the 1950s, CO₂ was measured intermittently using chemical titration methods on air collected near the ground. These data were numerous but heterogeneous. Callendar (1938) spent considerable effort correcting them, but they remained limited as a baseline climate record.

During the 1957–1958 International Geophysical Year, Charles David Keeling began continuous CO₂ measurements at Mauna Loa and the South Pole, using manometric calibration standards that he developed in addition to and commercial non-dispersive infrared analysers, achieving unprecedented precision. These measurements produced the iconic Keeling Curve (Keeling, 1960; Scripps Institution of Oceanography, 2026). Over subsequent decades, similar instruments were deployed at stations around the globe (see MACFARLANE, 2024). Today, the WMO’s Global Atmosphere Watch (GAW) and NOAA’s Global Monitoring Laboratory maintain coordinated networks using common calibration scales and intercomparisons (World Meteorological Organization, 2023, 2024). These data form the basis of the modern CO₂ curves in the figure. The cooperative network behind that global picture began in 1968, when NOAA’s carbon-cycle group, later the Geophysical Monitoring for Climatic Change programme and then the Climate Monitoring and Diagnostics Laboratory, started collecting air in glass flasks at remote sites and analysing it against shared calibration standards (Conway et al., 1994). As the network grew, the individual station



records were extended and integrated into a single, globally consistent series representing the marine boundary layer
 (Masarie and Tans, 1995); that global mean, plotted as the annual series in Fig. 4, begins in 1979. The rise at Mauna
 Loa had been unambiguous for two decades by then.

2.4.3 Other long-lived greenhouse gases: methane, nitrous oxide, sulfur hexafluoride

The record of the other long-lived gases begins in 1978. In July of that year the Atmospheric Lifetime Experiment
 (ALE) started high-frequency in situ measurements of nitrous oxide (N_2O) and the major halocarbons at five baseline
 stations, among them Kennaook / Cape Grim in Tasmania (Prinn et al., 2000). In the same year Cape Grim also
 began storing baseline air in steel tanks, an archive built so that species could be measured long after they were
 collected (Langenfelds et al., 1996). ALE has been superseded by Global Atmospheric Gases Experiment (GAGE)
 in 1986 and then Advanced Global Atmospheric Gases Experiment (AGAGE) in 1996.

Similar methods were applied to N_2O and halogenated gases including sulfur hexafluoride (SF_6), with parts-
 per-trillion detection limits. Unlike methane and nitrous oxide, which have large natural as well as anthropogenic
 sources, the halogenated gases and SF_6 are essentially synthetic, with negligible natural sources. Therefore, their
 mere detectable presence in the atmosphere is itself direct evidence of human activity. Modern flask and in situ
 systems routinely measure multiple species and isotopes on WMO-referenced calibration scales (Sierra et al., 2025;
 World Meteorological Organization, 2024). The Fig. 4 compresses these developments into a set of normalised curves
 (CH_4 , N_2O , and SF_6) that show how each gas has risen well above its pre-industrial baseline. Within three years
 of the continuous records beginning, methane was reported to be rising at about 2 per cent per year (Rasmussen
 and Khalil, 1981), and nitrous oxide at about 0.2 per cent per year across a global station network (Weiss, 1981),
 confirming earlier indications from stored air samples. For these gases, the trend was detected years before the
 records that document it were reconciled.

The earliest methane and nitrous oxide points in Fig. 4, from April 1978, come from the archive rather than from
 measurement at the time, and continuous in situ methane at these stations began only in the mid-1980s. Global
 monitoring became possible more widely from the early 1980s, once gas chromatography and clean flask sampling
 became standard. From 1983, NOAA and partner networks collected weekly flask samples and analysed them for
 methane, and the resulting 23-site network gave a globally distributed picture of its concentration and growth (Steele
 et al., 1987); the series was later extended and reanalysed into the global methane record in routine use (Dlugokencky
 et al., 1994).

2.4.4 Reconstructing past atmospheric composition from ice cores

Starting in the late twentieth century, climate science extended the atmospheric record far beyond the instrumental
 era by analysing air trapped in polar ice. When an ice core is drilled, the bubbles in each layer contain a sample of
 past atmosphere. Gas is extracted and analysed (Petit et al., 1999; Stauffer et al., 2002).



In 1996, detailed high-resolution records from Law Dome, Antarctica, an area of high snow-accumulation rates, were analysed to produce a precise millennium-long CO₂ series (Etheridge et al., 1996). A companion analysis extended the series to CH₄ (Etheridge et al., 1998). Later work refined and extended these records over the last two millennia (MacFarling Meure et al., 2006; Rubino et al., 2019). (Fig. 4b).

780 Deep Antarctic cores provide the longer glacial–interglacial context. The Vostok core extends greenhouse-gas and temperature histories over 420,000 years (Petit et al., 1999), while EPICA Dome C reaches back 800,000 years, showing pre-industrial CO₂ oscillating between about 172 and 300 ppm (Lüthi et al., 2008; Bereiter et al., 2015). Figure 4a contrasts this natural range with present-day concentrations, illustrating how far current CO₂ lies above late-Quaternary variability.

785 2.4.5 Ocean uptake and pH

Systematic measurement of ocean pH is considerably older than the acidification question. The earliest major survey was made by the German Atlantic expedition of the *Meteor* in 1925 to 1927, whose titration measurements of alkalinity and carbonate chemistry across the Atlantic were published by Wattenberg in 1933 (Brewer, 2013). In 1957, Revelle and Suess recognized that anthropogenic CO₂ uptake would alter ocean carbonate chemistry (Revelle
 790 and Suess, 1957). The Bermuda Atlantic Time-series Study (BATS) and the Hawaii Ocean Time-series (HOT) were both established in the late 1980s, HOT at Station ALOHA in 1988, and the Bermuda carbonate record reaches back to 1983 through measurements at the neighbouring Hydrostation S (Bates et al., 2014). Together they established long-term measurements of dissolved inorganic carbon, alkalinity, pCO₂ (partial pressure of carbon dioxide relevant for air-sea gas exchange) and pH (Karl and Lukas, 1996; Bates et al., 2014).

795 In 2007, trends significant against the seasonal and interannual variability of these sites were reported: at Bermuda over 1983 to 2005 (Bates, 2007) and at the European Station for Time-series in the Ocean in the subtropical North Atlantic (Santana-Casiano et al., 2007). In 2009, nearly two decades of observations at Station ALOHA revealed a clear downward trend in surface-ocean pH consistent with atmospheric CO₂ growth (Dore et al., 2009). Extending the result beyond individual stations required mapping sparse ship-based measurements across biomes: surface pH
 800 trends were estimated in seventeen of them for 1991 to 2011, a mean decline of 0.0018 ± 0.0004 units per year, although too few data exist in many biomes and the Arctic and high-latitude Southern Ocean are excluded (Lauvset et al., 2015).

Surface-ocean pH can also be reconstructed for centuries before direct measurements became available, using the boron-isotope ($\delta^{11}\text{B}$) composition of dated coral skeletons. Because dissolved borate and boric acid in seawater
 805 are pH-dependent, the boron preferentially incorporated by corals into their aragonite skeletons reflects the surface seawater pH at the time of growth (Hemming and Hanson, 1992; Foster, 2008). A $\delta^{11}\text{B}$ record from a New Caledonia *Diploastrea heliopora* coral now extends the tropical surface-pH series back to 1689 CE (Wu et al., 2018).

Since the early 1980s, accelerating greenhouse-gas-driven warming has become visible in the biological record as a time series of mass coral bleaching events in tropical and subtropical seas. Bleaching occurs when sustained



810 thermal stress causes corals to expel their symbiotic algae, leaving colonies pale and energy-deprived. In recent decades such events have shifted from being rarely reported to being a recurrent, globally monitored impact of marine heatwaves, with climate assessments identifying ocean warming as the primary driver of these large-scale events and ocean acidification as an important co-stress (NOAA Coral Reef Watch, 2025; Bindoff et al., 2019; IPCC, 2023). On individual reefs – particularly near population and resort centres – local, non-climatic stressors can
 815 dominate degradation and modulate bleaching: nutrient (nitrogen) pollution lowers the threshold for severe bleaching at low-to-moderate heat stress (Donovan et al., 2020), while sediment loading and physical destruction from coastal development and blast- or cyanide-fishing damage reefs outright. What identifies warming as the underlying climate signal is not the fate of any single reef but the basin-to-global synchrony of mass bleaching with satellite-tracked marine heatwaves; during the most extreme events, water quality and fishing pressure afford little resistance to the
 820 heat, and bleaching footprints track sea-surface-temperature anomalies rather than local disturbance (Hughes et al., 2017).

In 1998, a global bleaching event was documented, followed by further global-scale episodes in 2010 and 2014–2017. The latter was, at the time, the longest, most widespread and probably most damaging event on record, with satellite monitoring indicating that roughly two-thirds of the world’s coral reef area experienced bleaching-level heat stress
 825 (NOAA Coral Reef Watch, 2025). Bleaching is now observed across most reef regions (Eakin et al., 2019; Sully et al., 2019).

In 2023, a fourth global coral bleaching event began and was formally confirmed by NOAA and the International Coral Reef Initiative in April 2024; updated analyses from NOAA Coral Reef Watch show that between January 2023 and September 2025 bleaching-level heat stress affected about 84% of mapped coral-reef area. Mass bleaching
 830 has now been reported from more than eighty countries and territories, underscoring that the frequency, duration and spatial extent of bleaching events are increasing in step with anthropogenic ocean warming (NOAA Coral Reef Watch, 2025; NOAA, 2025a; International Coral Reef Initiative, 2025).

2.4.6 Section summary

The three measured greenhouse-gas records in Fig. 5 cross the four thresholds in a compressed period, and in an
 835 order that differs from the other families. Direct CO₂ measurement began in 1958, was institutionalised in NOAA’s cooperative flask network from 1968, and yielded a globally averaged series from 1979; the rise was already being recorded on calibrated instruments by 1960 (Keeling, 1960), so the observation precedes both the network and the global mean. The other long-lived gases follow the same pattern one observing generation later: the first in situ network and the Cape Grim air archive from 1978 (Langenfelds et al., 1996; Prinn et al., 2000), growth reported in
 840 1981 (Rasmussen and Khalil, 1981; Weiss, 1981), a weekly flask network from 1983 (Steele et al., 1987), and a global methane series in 1994 (Dlugokencky et al., 1994). Ocean pH inverts the family’s chronology, because the quantity is harder to measure than a gas concentration: surveyed as early as 1925 (Brewer, 2013), placed on a time-series

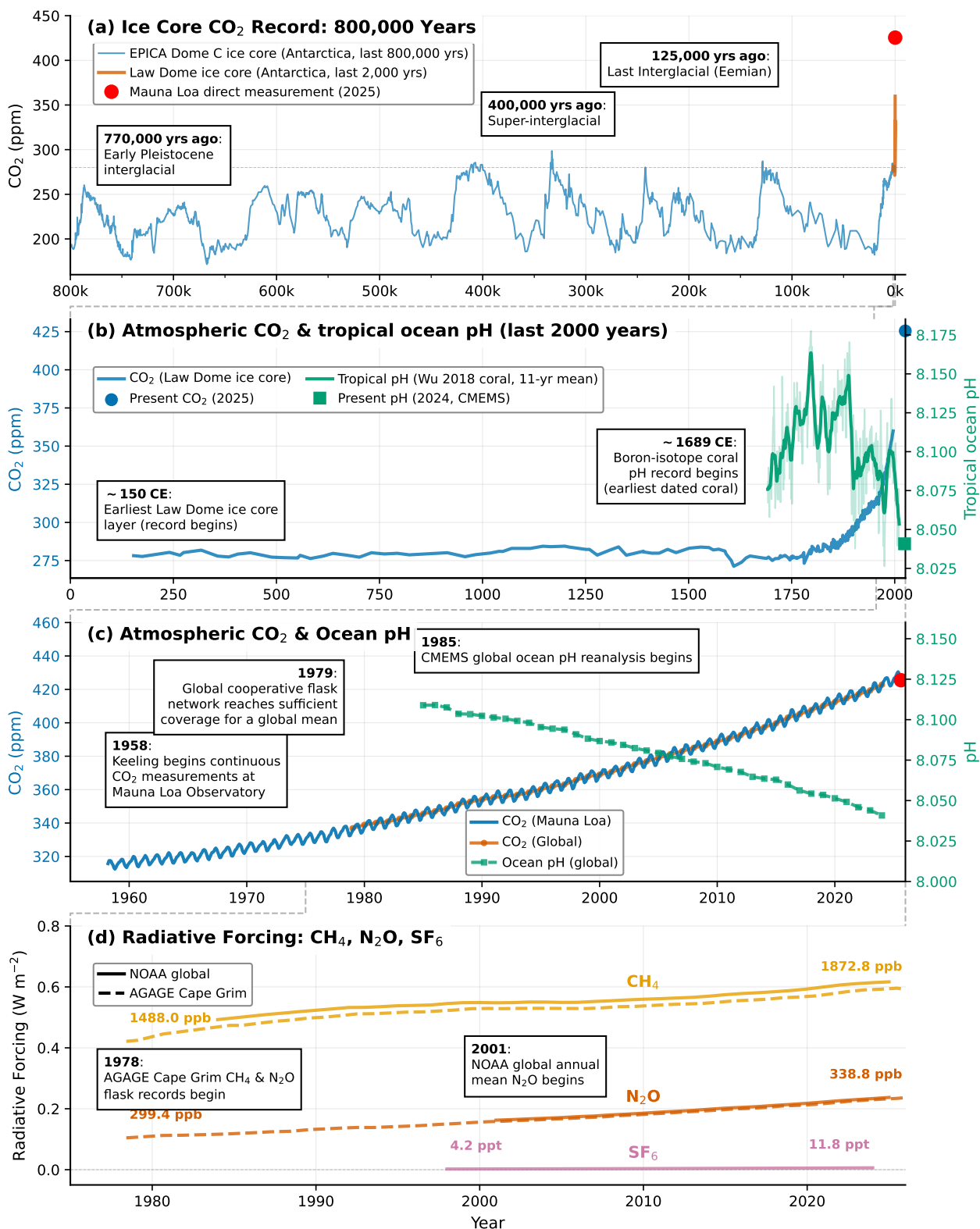




Figure 4. Atmospheric greenhouse gas concentrations, ocean acidification, and radiative forcing across four nested timescales. **(a)** Antarctic ice-core CO_2 over the last 800,000 years from the EPICA Dome C composite, overlaid with the Law Dome record for the last 2,000 years and the present-day Mauna Loa direct measurement. **(b)** Atmospheric CO_2 vs. tropical surface ocean pH over the last 2,000 years – Law Dome ice-core CO_2 (left axis) and pH reconstructed from coral ^{11}B at New Caledonia (Wu et al., 2018; the plotted values run 1692–2011 CE; right axis, anchored to the CMEMS modern surface mean 8.05). **(c)** Modern atmospheric CO_2 from Mauna Loa (monthly) and the global cooperative annual mean (1979–present), with global surface ocean pH on a secondary axis. **(d)** Radiative forcing (W m^{-2}) of CH_4 , N_2O , and SF_6 , computed from observed concentrations using the simplified expressions of the IPCC Third Assessment Report (IPCC, 2001), without their gas-overlap terms, referenced to pre-industrial values (CO_2 278 ppm, CH_4 722 ppb, N_2O 270 ppb, SF_6 ~ 0 ppt). The axis begins in 1975; the CH_4 and N_2O traces begin with the Cape Grim records in 1978 and the SF_6 trace with the NOAA global series in 1998.

footing at Bermuda from 1983 and Hawaii from 1988, detected at both in 2007 (Bates, 2007; Santana-Casiano et al., 2007), and mapped across most biomes only in 2015 (Lauvset et al., 2015).

845 3 Miscellaneous

3.1 External natural drivers and the recent warming signals

External natural drivers of climate (solar activity, Earth’s orbit, and volcanic eruptions) are important to understand, as they are often invoked by skeptics and deniers to suggest an alternative explanation for observed global warming.

From 1610, Harriot, Fabricius, Scheiner, and Galileo began telescopic sunspot observations (Arlt and Vaquero, 2020); Schwabe and Schwabe (1844) identified the approximately 11-year cycle, and Wolf later compiled the early
 850 observations into a continuous sunspot-number series extending back to 1700. Maunder (1894) documented the near absence of sunspots between 1645 and 1715, a period known as the “Maunder Minimum”. Eddy (1976) revisited the Maunder Minimum, using ^{14}C tree-ring proxies, and linked it to cool intervals in the so-called Little Ice Age.

The orbital theory of climate has an equally long lineage, with a clear division between those who conceived it
 855 and those who quantified it. Adhémar (1842) first proposed that slow changes in Earth’s orbit pace the ice ages, attributing them to the precession of the equinoxes; Croll (1875) developed the idea, introducing the role of orbital eccentricity and producing the first calculations of the resulting changes in insolation (incoming solar radiation). Milanković (1941) placed the theory on a rigorous quantitative footing, computing the variations in high-latitude summer insolation produced by three orbital parameters – eccentricity ($\sim 100,000$ -year period), obliquity ($\sim 41,000$
 860 years), and precession ($\sim 23,000$ years) – over hundreds of thousands of years. Empirical confirmation followed when Hays, Imbrie, and Hays et al. (1976) detected these predicted periodicities in deep-sea oxygen-isotope records, and orbital pacing remains the leading explanation for the glacial–interglacial cycles visible in the 800,000-year records of Figures 3 and 4 (Petit et al., 1999). These mechanisms cannot, however, explain the recent warming. Orbital



forcing varies over tens of thousands of years and is effectively constant across a century or two; moreover, Northern Hemisphere summer insolation has declined slowly since its early-Holocene maximum, so the present orbital tendency is, if anything, weakly towards cooling – the opposite sign to the observed warming (Berger and Loutre, 1991).

Direct satellite measurement of total solar irradiance (TSI) began with Nimbus-7 in 1978 and has continued through ACRIM, ERBE, VIRGO and SORCE/TIM (Kopp and Lean, 2011), and since 2017 TSIS-1. These records establish what astronomical forcing does and does not do. On shorter timescales the 11-year cycle produces a global mean signal of order 0.1°C (Lean et al., 1995). Grand minima such as the Maunder coincide with cool excursions of a few tenths of a degree Celsius, but irradiance in those centuries is known only from proxy reconstructions, whose successive versions have substantially reduced the estimated Maunder-era deficit (IPCC, 2021); attribution studies now assign the cold centuries of the Little Ice Age primarily to volcanic activity, with at most a minor solar contribution (Schurer et al., 2014).

Volcanic eruptions are the remaining major natural driver, and on the multidecadal-to-century timescales over which the recent warming has unfolded the most important one (Robock, 2000; Schurer et al., 2014). Large explosive eruptions inject sulphur gases into the stratosphere, where they convert to sulphate aerosols that reflect sunlight and cool the surface, with a residence time of about a year; superposed-epoch analysis of the largest eruptions since Krakatau (1883) shows peak global cooling of one to two tenths of a degree Celsius roughly a year after each event (Robock, 2000). Clustered eruptions can reach much further: precisely dated Arctic records and model simulations indicate that the Little Ice Age began abruptly between 1275 and 1300 CE, following a sequence of large sulphur-rich eruptions, and that sea-ice and ocean feedbacks sustained the cooling for centuries afterwards (Miller et al., 2012). Quiescence works in the opposite direction: after the 1912 Novarupta (Katmai) eruption in Alaska, no comparable stratospheric injection occurred until Agung in 1963, and this half-century lull contributed to the warming observed over the early twentieth century (Robock, 2000). Volcanic activity therefore cannot explain the past half-century of warming: its forcing is episodic, with no long-term trend, and its direct effect is cooling. The satellite era contains only two climatically significant sulphate-rich eruptions (El Chichón in 1982 and Pinatubo in 1991), each of which briefly cooled the planet while greenhouse gas concentrations continued to rise.

For the recent warming, none of these drivers can account for the observed trend; taken together, they point the wrong way. Satellite TSI has been flat or slightly declining since the late 1970s while global mean surface temperature has risen by approximately 0.6°C , so solar and surface-temperature trends have moved in opposite directions across the satellite era (Lockwood and Fröhlich, 2007, 2008). The observed vertical structure (warming below, stratospheric cooling above; Fig. 1, Sect. 2.1) is incompatible with a solar driver and is the canonical greenhouse fingerprint (Santer et al., 1996; Tett et al., 1996; Vinnikov et al., 1996; Santer et al., 2023). In other words, detailed observations show that the recent, observed warming cannot be explained by exogenous natural drivers. This is why the IPCC AR6 attributes essentially all of the long-term warming to human influence: solar and volcanic activity combined changed global mean surface temperature by only -0.1° to $+0.1^{\circ}\text{C}$ from 1850–1900 to 2010–2019, whereas human-caused warming over the same interval has a best estimate of 1.07°C (likely range 0.8 – 1.3°C), essentially the whole of



the observed $\sim 1.1^{\circ}\text{C}$ (IPCC, 2021). That near-equality is itself the residual of two large, partly offsetting human influences: well-mixed greenhouse gases alone would have produced $1.0\text{--}2.0^{\circ}\text{C}$ of warming, of which a substantial part has been masked by the cooling of anthropogenic aerosols ($0.0\text{--}0.8^{\circ}\text{C}$). Aerosols therefore do not weaken the attribution but reconcile the magnitude of greenhouse forcing with the somewhat smaller observed warming. The effect of aerosols comparable in magnitude to the greenhouse gases, though opposite in sign and far more uncertain, has been recognised since the early 1970s (Rasool and Schneider, 1971) and was quantified for sulphate by Charlson et al. (1992), with AR6 assessing total aerosol effective radiative forcing (1750–2014) at $1.3 [2.0 \text{ to } 0.6] \text{ W m}^{-2}$ (IPCC, 2021; Bellouin et al., 2020). The natural aerosol background, such as volcanic sulphate, produces only brief cooling episodes, and the dust and sea-salt load shows no sustained trend, so natural aerosols cool the mean climate but cannot have driven a multidecadal warming trend (IPCC, 2021).

3.1.1 Phenological and biophysical proxies of warming

Phenological records independently corroborate the warming seen in the thermometer and satellite records (Macfarlane, 2021). Three series in particular have multi-century baselines and show sharp departures coinciding with the accelerated warming of recent decades.

Kyoto cherry blossom (*Prunus jamasakura*) full-flowering dates have been compiled from imperial diaries and chronicles dating back to 812 CE (Aono and Kazui, 2008; Aono and Saito, 2010). It has a temperature sensitivity roughly corresponding to 4 days per $^{\circ}\text{C}$ (Aono and Kazui, 2008). Kyoto's full flowering on 26 March 2021 was the earliest in the 1,200-year record, and a formal attribution apportions an ~ 11 -day advance in mean flowering date to combined human influence (Christidis et al., 2022).

European grape-harvest dates, principally the homogenised Beaune series, extend to 1354 from medieval account-books and parish records (Chuine et al., 2004; Daux et al., 2012; Labbé et al., 2019). Harvest date has a sensitivity of 6 days per $^{\circ}\text{C}$ (Cook and Wolkovich, 2016). The Beaune harvest in 1988–2018 was, on average, 13 days earlier than across the preceding 634 years (Labbé et al., 2019).

The records of the freeze and breakup dates for Northern Hemisphere lakes and rivers, several spanning more than 300 years, are aggregated in the NSIDC Global Lake and River Ice Phenology Database (Benson et al., 2000; Magnuson et al., 2000; Sharma et al., 2022). On average, seasonally ice-covered lakes lose 9 to 10 days of ice duration per $^{\circ}\text{C}$ in seasonally ice-covered lakes (Grant et al., 2021). Northern Hemisphere lake-ice trends have nearly doubled when the Magnuson et al. (2000) record is extended to 2019 (Sharma et al., 2021), and have been formally attributed to anthropogenic forcing (Grant et al., 2021).

Each series also encodes substantial internal climate variability (North Atlantic Oscillation, atmospheric blocking, Pacific Decadal Oscillation, El Niño–Southern Oscillation, East Asian monsoon), and apparent early-20th-century trends are partly artefactual. The Kyoto record is biased by urban heat island warming over central Kyoto, with roughly half of the observed advance in flowering date attributable to urbanisation rather than large-scale forcing (Christidis et al., 2022); grape-harvest series carry pre-1900 calibration heterogeneity and changes in viticultural



practice (Daux et al., 2012; Labbé et al., 2019); and lake-ice phenology is sensitive to network sparsity and the dropout of southern lakes that lose ice entirely (Newton and Mullan, 2021; Sharma et al., 2022). The unambiguous, large-amplitude signal therefore emerges most clearly in the post-1980 portion of every series.

4 Conclusions

Between the theoretical understanding of the physical principles of the greenhouse effect, established in the nineteenth century (Weart, 2008), and the recognition of climate change as a problem at the national (Oreskes et al., 2023) and international level (World Meteorological Organization, 1979) in the 1960s and '70s, lies a long period in which the evidence and understanding was built. This interval is the subject of the present paper. Its central feature is that the relevant indicators did not become mature simultaneously; each crossed the threshold of reliable, globally resolved measurement in its own time. There was, accordingly, no single moment at which the evidence of anthropogenic climate change “matured”. Fig. 5 summarises that sequence. For each line of evidence it marks the years at which the record crossed four thresholds: from the first systematic measurements to standardisation, to global coverage, and to detected trend. Sometimes the sequence is not in that order, and in some cases we have made an expert judgement call about individual events. Yet, the overall trend in recognition and maturation of these observations is evident.

4.1 Convergence: from local records to a global observing system

Across all four indicator families, the timelines share a common institutional trajectory. The earliest observations were typically local and often motivated by concerns only tangentially related to global climate (if at all): weather diaries kept for agriculture and health, tide gauges installed for navigation and harbour management, ship-based measurements collected for operational oceanography, and early cryospheric notes tied to exploration or local infrastructure. In retrospect, many of these began as idiosyncratic bookkeeping exercises – useful locally, heterogeneous in method, and hard to compare across places.

Over time, those observations were standardised (e.g. in instruments, exposures, sampling practices, calibration, and metadata), taken up as routine state responsibilities, and integrated into coordinated international infrastructures. This process was not synchronous. Indicators that were operationally useful and relatively cheap to measure – surface air temperature, coastal sea level, shipboard sea-surface temperature – go back further than those that required specialised logistics, expensive and technologically sophisticated observing platforms (e.g. ice-sheet mass balance, hemispheric snow mapping, deep-ocean heat content), or demanded laboratory frameworks and stable calibration scales (i.e. trace greenhouse gases).

Certain technological advances caused step changes, such as radiosonde networks in 1930s, the 1992 onset of precision satellite altimetry for global sea level, and the early-2000s coupling of Argo with satellite gravimetry and altimetry to close budgets (Durre et al., 2006; WCRP Global Sea Level Budget Group, 2018). These discontinu-



The staggered maturation of the evidence

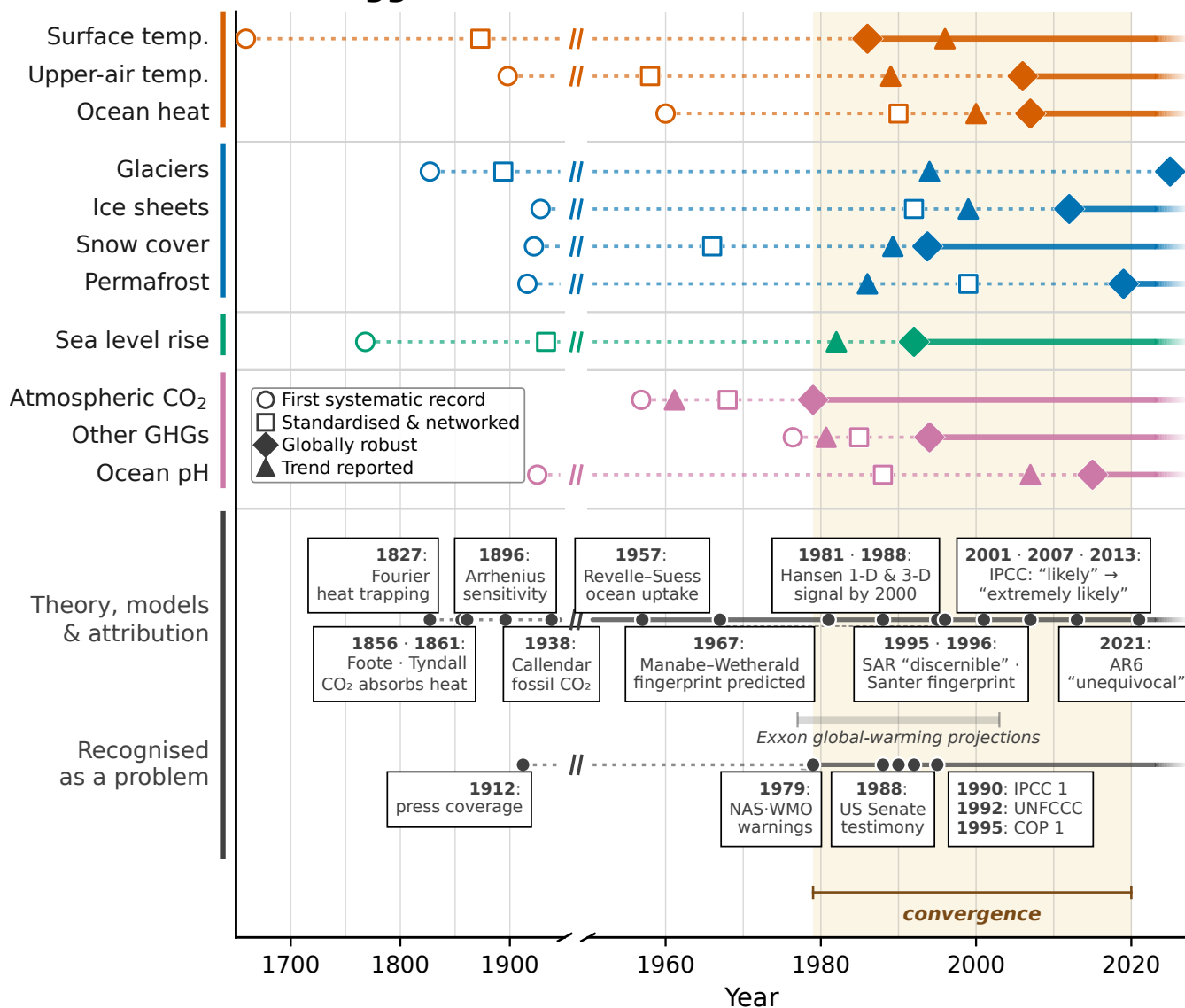




Figure 5. Every mark is the year a line of evidence crossed one of four thresholds: first systematic record (circle), standardised and networked observation (square), near-global reconciled record (diamond), first published trend in that record (triangle). Rails turn solid once globally robust; the axis breaks at 1950. The families. Temperature has the deepest roots: measured since 1659, standardised by 1873, synthesised globally in 1986, trend reported in 1996. Ocean heat is heat content, measurable globally only from 1960. The cryosphere, noticed early, was reconciled late: ice sheets 2012, permafrost 2019, glaciers 2025. Sea level is one indicator on two successive systems: tide gauges from 1768, altimetry from 1992. Trends preceded finished records. In ten of eleven rows the triangle precedes the diamond. The triangle marks a published trend, not a formal test against natural variability. Permafrost is extreme: borehole profiles yielded evidence of warming in 1986, thirty-three years before its global synthesis. Convergence without synchrony. Twenty of twenty-two diamonds and triangles fall in the shaded band, 1979–2020; the exceptions bracket it: CO₂ detected by 1960, glaciers reconciled in 2025. No single moment delivered the evidence. Foresight. Manabe and Wetherald’s 1967 model predicted the tropospheric-warming, stratospheric-cooling fingerprint; Hansen’s projections placed its emergence by 2000, as did Exxon’s projections (grey bar); the IPCC found human influence “discernible” in 1995, just before Santer’s fingerprint (arrow beneath the rail), and by 2021 “unequivocal”. Recognition (bottom lane) runs from 1912 press coverage to COP 1 (1995). Conventions. Threshold years are judgements; the section summaries give the anchor for each, and overlapping marks are nudged apart by at most two years. Abbreviations: GHG: greenhouse gases; CO₂: carbon dioxide.

ities are not weaknesses; they are signatures of technical and institutional advances that turned previously partial indicators into globally coherent ones.

By the late twentieth century, most of the canonical indicators had become global or near-global, supported by large sensor arrays and intercomparison projects that transformed raw observations into climate records (Zillman, 2018; Roemmich and Owens, 2000; Nerem et al., 2018). In other words, the “global signal” is not simply a property of the global climate system; it is also a property of observing systems that were deliberately built to see it.

4.2 Robustness: why the case rests on no single record

While many people are now familiar with the Keeling curve, which shows the rise of atmospheric CO₂ over time, the contemporary climate case is not an argument from a single curve; it is an *ensemble* of measurements that were developed for different purposes, by different communities, using different instruments, yet which converge on the same physical narrative. In this sense, it meets the standard that William Whewell described in the 19th century as a “consilience of inductions” (Laudan, 1971; Snyder, 2023), a standard similar to what one might look for in a court of law (Ho, 2021). The strength of the case is, indeed, in the fact that different, independent lines of evidence, initially studied by different people for different reasons, all point to the same core conclusions.

It may be useful to ask: which line of observation, if removed, would undermine the central conclusion of climate science? For the conclusion that the climate is warming and that the warming is anthropogenic, no record from the indicator families surveyed meets that test. Any one of these records – the Mauna Loa CO₂ record, the satellite altimetry of sea level, the Argo network, the IMBIE reconciliation of ice-sheet mass balance, and the radiosonde



and satellite records of upper-air temperature – could be set aside and the remaining indicators would still establish the same conclusion within their independent uncertainty budgets. The case is over-determined. That redundancy, rather than the strength of any single decisive observation, is the structural feature of the evidence base.

Some indicators are especially diagnostic in the sense that they speak not only to change, but to the cause. The vertical temperature structure – warming in the lower atmosphere paired with cooling in the stratosphere – follows directly from greenhouse-gas radiative physics and is a canonical “fingerprint” of greenhouse forcing (IPCC, 2021). In the same spirit, the sea-level budget framework shows that the observed rise in global mean sea level in the altimeter era can be quantitatively accounted for, within uncertainty, by thermal expansion plus land-ice mass loss, providing a cross-checked link between warming and one of its most societally relevant consequences (WCRP Global Sea Level Budget Group, 2018). Ice-core records provide another unusually “clean” constraint: they turn the atmosphere itself into an archive, showing that current CO₂ concentrations lie outside the late-Quaternary range, and that the ongoing rise is rapid relative to the paced variability captured in glacial-interglacial cycles (Petit et al., 1999; Lüthi et al., 2008). Each of these lines of evidence is compelling on its own; taken together, they form a repertoire of observations that is robust, mutually reinforcing, and unusually easy to communicate because it is rooted in time series that can be “read” visually.

This review has deliberately foregrounded observations, but observations do not speak for themselves, and the most diagnostic results above are comparisons between measurements and physically based models. The greenhouse “fingerprint” is compelling precisely because the contrasting pattern of tropospheric warming and stratospheric cooling was a model prediction (Manabe and Wetherald, 1967) before it was an observation, and formal detection-and-attribution is by construction a model–observation comparison (Santer et al., 1996, 2023; IPCC, 2021). Closure of the sea-level and Earth-energy budgets relies on models of thermal expansion and of glacial-isostatic adjustment (Peltier, 2004; WCRP Global Sea Level Budget Group, 2018). Ice cores become climate archives only after firn-densification and ice-flow models resolve the gas-age/ice-age offset and the depth–age relationship (Veres et al., 2013); where those models fail – as in the disturbed basal ice of the oldest cores – such intervals are appropriately set aside as causal evidence until data or models improve. The principal remaining uncertainty in projected sea-level rise is set not by missing observations but by incompletely understood ice-sheet dynamics (IPCC, 2021). Observations and models are therefore not rivals but mutually reinforcing: models give observations their interpretive reach, while observations test, constrain, and sometimes refute models (Oreskes et al., 1994; Edwards, 2010).

4.3 Knowability: when the core claims became knowable

There is no single moment in which we can say “we” (or “they”) knew. Some public awareness that burning fossil fuels could warm the planet predated both the coalescence of the scientific evidence base and the scientific community’s communication of its urgency, in some cases by decades. That awareness was uneven and geographically circumscribed, so it would overstate the record to say that “humanity” knew. How circumscribed remains an open question, because the scholarship on early public awareness rests largely on English-language, and mostly American,

sources (Weart, 2008; Fleming, 2007; Howe, 2014). However, by the later decades of the twentieth century, political leaders in the industrialised world and the heads of major fossil-fuel companies were in a position to know what the science showed.

1020 We can identify some degree of public awareness as early as the early 20th century. A 1912 item in the U.S. magazine *Popular Mechanics* – reprinted in newspapers as distant as New Zealand – already told readers that the world’s coal furnaces were making “the air a more effective blanket for the earth”, with effects that “may be considerable in a few centuries” (Molena, 1912). Human-caused warming was discussed in the mainstream press through the 1930s (Weart, 2008). By the late 1940s and early 1950s global warming was back on the public agenda, 1025 with the popular press following the scientists: between 1950 and 1956 *Time*, the *Saturday Evening Post*, and the *New York Times Magazine* all covered the warming trend; in 1953 *Time* and the *New York Times Magazine* tied it explicitly to industrial carbon dioxide, citing Plass’s and Callendar’s figures, respectively (Fleming, 2007). In the years that followed, the message reached mass American audiences: Frank Capra’s television film *The Unchained Goddess* (1958), the classroom weekly *My Weekly Reader* (“Carbon dioxide acts like a heat trap”, 1959), and magazines from 1030 *Fortune* in 1965 to *Sports Illustrated* in 1970 (Oreskes et al., 2023). Sustained political attention took longer: climate change entered U.S. environmental politics only around 1970, remained largely within the scientific community’s purview until the mid-1980s, and reached the political mainstream in 1988 (Howe, 2014).

By the late 1970s, the accumulation of scientific evidence was sufficient for scientific bodies to begin to issue warnings. In the United States, the U.S. National Academy of Sciences issued its first authoritative assessment of 1035 CO₂-induced warming in 1979 (Ad Hoc Study Group on Carbon Dioxide and Climate et al., 1979). That same year, the First World Climate Conference, convened by the World Meteorological Organization, issued a declaration stating that it was now “urgently necessary” for the “nations of the world” to improve scientific understanding of climate, but also to “take full advantage” of what was already known, “to foresee and to prevent potential man-made changes in climate that might be adverse to the well-being of humanity” (World Meteorological Organization, 1979).

1040 In the years to follow, numerous reports were issued, including a second report from the NAS, a report from the U.S. Environmental Protection Agency in 1983 (National Research Council, 1983; Seidel and Keyes, 1983), the first report of the Intergovernmental Panel on Climate Change in 1990 (IPCC, 1990). Critically, the U.N. Framework Convention on Climate Change was adopted in New York in May 1992 and opened for signature at Rio de Janeiro that June (United Nations, 1992), based on the scientific evidence which, by that point, was broadly understood by 1045 many scientists and policymakers to warrant action. The first Conference of the Parties to the Convention met in Berlin from 28 March to 7 April 1995 and adopted the Berlin Mandate (UNFCCC, 1995), which opened negotiations on a protocol or another legal instrument and directed that they be completed in time for the third session; the Kyoto Protocol followed in 1997 (UNFCCC, 1997).

The timelines presented here underscore a point that is often blurred in public debate: the late twentieth-century 1050 observing systems did not create the basic understanding of anthropogenic climate change; they made that understanding inescapable. The mechanism, the direction of change, and even approximate magnitudes were in place well



before the observing systems that would document them were complete, as the preceding sections set out and Fig. 5 summarises. Leading U.S. scientists communicated to the U.S. government that they foresaw major adverse, even catastrophic, impacts (Oreskes et al., 2023). By the late 1970s and early 1980s, quantitative projections of future warming were being produced not only in academic settings but inside parts of the fossil-fuel industry: archival analysis shows that many of the projections reported by Exxon and ExxonMobil scientists between 1977 and 2003, in internal documents and in the peer-reviewed literature alike, were consistent with the warming that subsequently occurred (Supran et al., 2023). Key elements of the physical case were therefore knowable, and in important venues known, well before the fully global observing system came online (Weart, 2008; Edwards, 2010).

The formal assessment process certified this understanding later than the underlying science warranted. The First Assessment Report of 1990 could conclude only that the observed warming was “broadly consistent with predictions of climate models” yet “of the same magnitude as natural climate variability”, and it judged unequivocal detection of the enhanced greenhouse effect “not likely for a decade or more” (IPCC, 1990). Five years later the Second Assessment Report found a discernible human influence. The two conclusions rested on different achievements. Detection, showing that observed trends had emerged from the noise of natural variability, codified an observational case that was already well established. Attribution, formally assigning those trends to human influence, was genuinely new, and it turned on pattern-based fingerprint analysis matching the observed vertical and spatial structure of temperature change to the response simulated by forced climate models (Santer et al., 1996). That literature was so recent, and authored by so few groups, that the report’s detection-and-attribution chapter did not summarise a settled field so much as perform the synthesis itself: its central conclusion was approved at the Madrid plenary of Working Group I in November 1995, months before the keystone fingerprint paper appeared in print. The credibility of the finding, and its political and legal force, rests on that pairing of observational detection with model-based attribution.

4.4 Implications: sustaining the observing commons

Scientifically, the case for anthropogenic climate change is strong not because any single indicator is perfect, but because imperfect indicators – built independently, motivated differently, and cross-validated in the modern era – converge on a coherent physical account. Institutionally, the measurement systems that make this convergence visible are a form of public infrastructure: they depend on stable support, open access, and international coordination. If the twentieth-century story is one of scaling up – from local bookkeeping to planetary monitoring – then the twenty-first-century challenge is to maintain that capacity, fill remaining gaps (especially in subsurface and polar domains), and preserve the evidentiary record as something that can be inspected and trusted.

In that sense, the timelines assembled here double as a timeline of responsibility: they show not only how we came to know what we know, but also how long we have been in a position to act on it – and what kinds of institutions (scientific, political, and legal) are required to keep that knowledge legible in the future.



1085 Like most scientific knowledge, the strength of climate science is not the product of a single “discovery moment”,
 or even of a single important line of investigation, much less the work of an individual genius. Rather, it is the result
 of the progressive construction of measurement systems, interpreted through and tested against physically based
 models, by a broad community of researchers – each mastering a part of the problem, and eventually discovering how
 the parts connect – whose independent efforts nonetheless converge to render global change observable, measurable,
 1090 comparable, and, ultimately, knowable.

Data availability. No new data were generated for this review. It draws only on publicly available datasets and published
 literature, each cited at the point of use and listed in the reference list.

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 manuscript. AK compiled the timelines and produced the figures. Both authors reviewed and approved the submitted version.

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 1105 observational records and dates on which the figures rest; to write the plotting code that produced Figs. 1–5; and to check
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 Every date, number, quotation, and citation reported here was checked by the authors against the cited source.

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1110 References

- Abraham, J. P., Baringer, M., Bindoff, N. L., Boyer, T., Cheng, L. J., Church, J. A., Conroy, J. L., Domingues, C. M., Fasullo, J. T., Gilson, J., Goni, G., Good, S. A., Gorman, J. M., Gouretski, V., Ishii, M., Johnson, G. C., Kizu, S., Lyman, J. M., Macdonald, A. M., Minkowycz, W. J., Moffitt, S. E., Palmer, M. D., Piola, A. R., Reseghetti, F., Schuckmann, K., Trenberth, K. E., Velicogna, I., and Willis, J. K.: A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change, *Reviews of Geophysics*, 51, 450–483, <https://doi.org/10.1002/rog.20022>, 2013.
- 1115 Ad Hoc Study Group on Carbon Dioxide and Climate, Climate Research Board, Assembly of Mathematical and Physical Sciences, and National Research Council: Carbon Dioxide and Climate: A Scientific Assessment, National Academies Press, Washington, D.C., <https://doi.org/10.17226/12181>, 1979.
- Adhémar, J.: Révolutions de la mer, déluges périodiques, Lacroix-Comon, Paris, <https://catalog.hathitrust.org/Record/006223443>, 1842.
- 1120 Anderson, K.: Predicting the Weather: Victorians and the Science of Meteorology, University of Chicago Press, Chicago, 2005.
- Aono, Y. and Kazui, K.: Phenological data series of cherry tree flowering in Kyoto, Japan, and its application to reconstruction of springtime temperatures since the 9th century, *International Journal of Climatology*, 28, 905–914, <https://doi.org/10.1002/joc.1594>, 2008.
- 1125 Aono, Y. and Saito, S.: Clarifying springtime temperature reconstructions of the medieval period by gap-filling the cherry blossom phenological data series at Kyoto, Japan, *International Journal of Biometeorology*, 54, 211–219, <https://doi.org/10.1007/s00484-009-0272-x>, 2010.
- Arlt, R. and Vaquero, J. M.: Historical sunspot records, *Living Reviews in Solar Physics*, 17, 1, <https://doi.org/10.1007/s41116-020-0023-y>, 2020.
- 1130 Arrhenius, S.: XXXI. On the influence of carbonic acid in the air upon the temperature of the ground, *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 41, 237–276, <https://doi.org/10.1080/14786449608620846>, 1896.
- Bamber, J. L., Oppenheimer, M., Kopp, R. E., Aspinall, W. P., and Cooke, R. M.: Ice sheet contributions to future sea-level rise from structured expert judgment, *Proceedings of the National Academy of Sciences*, 116, 11 195–11 200, <https://doi.org/10.1073/pnas.1817205116>, 2019.
- 1135 Barry, R. and Gan, T. Y.: The Global Cryosphere: Past, Present and Future, Cambridge University Press, Cambridge, <https://doi.org/10.1017/CBO9780511977947>, 2011.
- Bates, N. R.: Interannual variability of the oceanic CO₂ sink in the subtropical gyre of the North Atlantic Ocean over the last 2 decades, *Journal of Geophysical Research: Oceans*, 112, 2006JC003 759, <https://doi.org/10.1029/2006JC003759>, 2007.
- Bates, N. R., Astor, Y. M., Church, M. J., Currie, K., and Dore, J. E.: A Time-Series View of Changing Ocean Chemistry Due to Ocean Uptake of Anthropogenic CO₂ and Ocean Acidification, *Oceanography*, 27, 126–141, <https://doi.org/10.5670/oceanog.2014.16>, 2014.
- 1140 Bellouin, N., Quaas, J., Gryspeerdt, E., Kinne, S., Stier, P., Watson-Parris, D., Boucher, O., Carslaw, K. S., Christensen, M., Daniau, A.-L., Dufresne, J.-L., Feingold, G., Fiedler, S., Forster, P., Gettelman, A., Haywood, J. M., Lohmann, U., Malavelle, F., Mauritsen, T., McCoy, D. T., Myhre, G., Mülmenstädt, J., Neubauer, D., Possner, A., Rugenstein, M., Sato, Y., Schulz, M., Schwartz, S. E., Sourdeval, O., Storelvmo, T., Toll, V., Winker, D., and Stevens, B.: Bounding Global Aerosol
- 1145



- Radiative Forcing of Climate Change, *Reviews of Geophysics*, 58, e2019RG000660, <https://doi.org/10.1029/2019RG000660>, 2020.
- Benson, B., Magnuson, J., and Sharma, S.: Global Lake and River Ice Phenology Database, <https://doi.org/10.7265/N5W66HP8>, 2000.
- 1150 Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T. F., Fischer, H., Kipfstuhl, S., and Chappellaz, J.: Revision of the EPICA Dome C CO₂ record from 800 to 600 kyr before present, *Geophysical Research Letters*, 42, 542–549, <https://doi.org/10.1002/2014GL061957>, 2015.
- Berger, A. and Loutre, M. F.: Insolation values for the climate of the last 10 million years, *Quaternary Science Reviews*, 10, 297–317, [https://doi.org/10.1016/0277-3791\(91\)90033-Q](https://doi.org/10.1016/0277-3791(91)90033-Q), 1991.
- 1155 Bindoff, N. L., Cheung, W. W. L., Kairo, J. G., Arístegui, J., Guinder, V. A., Hallberg, R., Hilmi, N., Jiao, N., Karim, M. S., Levin, L., O'Donoghue, S., Purca Cuicapusa, S. R., Rinkevich, B., Suga, T., Tagliabue, A., and Williamson, P.: Changing ocean, marine ecosystems, and dependent communities, in: IPCC special report on the ocean and cryosphere in a changing climate, edited by Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M., pp. 447–587, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, <https://doi.org/10.1017/9781009157964.007>, 2019.
- 1160 Biskaborn, B. K., Lanckman, J.-P., Lantuit, H., Elger, K., Streletskiy, D. A., Cable, W. L., and Romanovsky, V. E.: The new database of the Global Terrestrial Network for Permafrost (GTN-P), *Earth System Science Data*, 7, 245–259, <https://doi.org/10.5194/essd-7-245-2015>, 2015.
- Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., 1165 Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johansson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckman, J.-P., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramos, M., Sannel, A. B. K., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M., and Lantuit, H.: Permafrost is warming at a global 1170 scale, *Nature Communications*, 10, 264, <https://doi.org/10.1038/s41467-018-08240-4>, 2019.
- Boening, C., Lebsock, M., Landerer, F., and Stephens, G.: Snowfall-driven mass change on the East Antarctic ice sheet, *Geophysical Research Letters*, 39, <https://doi.org/10.1029/2012GL053316>, 2012.
- Brewer, P. G.: A short history of ocean acidification science in the 20th century: a chemist's view, *Biogeosciences*, 10, 7411–7422, <https://doi.org/10.5194/bg-10-7411-2013>, 2013.
- 1175 Brown, R. D.: Northern Hemisphere Snow Cover Variability and Change, 1915–97, *Journal of Climate*, 13, 2339–2355, [https://doi.org/10.1175/1520-0442\(2000\)013<2339:NHSCVA>2.0.CO;2](https://doi.org/10.1175/1520-0442(2000)013<2339:NHSCVA>2.0.CO;2), 2000.
- Brown, R. D. and Robinson, D. A.: Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty, *The Cryosphere*, 5, 219–229, <https://doi.org/10.5194/tc-5-219-2011>, 2011.
- Callendar, G. S.: The artificial production of carbon dioxide and its influence on temperature, *Quarterly Journal of the Royal Meteorological Society*, 64, 223–240, <https://doi.org/10.1002/qj.49706427503>, 1938.
- 1180 Cazenave, A. and Nerem, R. S.: Present-day sea level change: Observations and causes, *Reviews of Geophysics*, 42, 2003RG000139, <https://doi.org/10.1029/2003RG000139>, 2004.



- Challenger Expedition (1872-1876), Great Britain., Buchan, A., Huxley, T. H., Murray, J., Nares, G. S., Nares, G. S., Pelseneer, P., Thomson, C. W., Thomson, F. T., Thomson, F. T., and Challenger (Ship): Report on the scientific results of the voyage of H.M.S. Challenger during the years 1873-76 under the command of Captain George S. Nares ... and the late Captain Frank Tourle Thomson, R.N, Neill, Edinburgh, <https://doi.org/10.5962/bhl.title.6513>, 1880.
- Chang, H.: Inventing Temperature: Measurement and Scientific Progress, Oxford University Press New York, 1 edn., <https://doi.org/10.1093/0195171276.001.0001>, 2004.
- Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R. D., Coakley, J. A., Hansen, J. E., and Hofmann, D. J.: Climate Forcing by Anthropogenic Aerosols, *Science*, 255, 423–430, <https://doi.org/10.1126/science.255.5043.423>, 1992.
- Cheng, L., Trenberth, K. E., Fasullo, J., Boyer, T., Abraham, J., and Zhu, J.: Improved estimates of ocean heat content from 1960 to 2015, *Science Advances*, 3, e1601545, <https://doi.org/10.1126/sciadv.1601545>, 2017.
- Christidis, N., Aono, Y., and Stott, P. A.: Human influence increases the likelihood of extremely early cherry tree flowering in Kyoto, *Environmental Research Letters*, 17, 054051, <https://doi.org/10.1088/1748-9326/ac6bb4>, 2022.
- Chuine, I., Yiou, P., Viovy, N., Seguin, B., Daux, V., and Ladurie, E. L. R.: Grape ripening as a past climate indicator, *Nature*, 432, 289–290, <https://doi.org/10.1038/432289a>, 2004.
- Clarke, G. K.: A short history of scientific investigations on glaciers, *Journal of Glaciology*, 33, 4–24, <https://doi.org/10.3189/S0022143000215785>, 1987.
- Clow, G. D.: Temperature data acquired from the DOI/GTN-P Deep Borehole Array on the Arctic Slope of Alaska, 1973–2013, *Earth System Science Data*, 6, 201–218, <https://doi.org/10.5194/essd-6-201-2014>, 2014.
- Conway, T. J., Tans, P. P., Waterman, L. S., Thoning, K. W., Kitzis, D. R., Masarie, K. A., and Zhang, N.: Evidence for inter-annual variability of the carbon cycle from the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory Global Air Sampling Network, *Journal of Geophysical Research: Atmospheres*, 99, 22 831–22 855, <https://doi.org/10.1029/94JD01951>, 1994.
- Cook, B. I. and Wolkovich, E. M.: Climate change decouples drought from early wine grape harvests in France, *Nature Climate Change*, 6, 715–719, <https://doi.org/10.1038/nclimate2960>, 2016.
- Croll, J.: Climate and time in their geological relations: a theory of secular changes of the earth's climate, Daldy, Isbister & Co., London, <https://archive.org/details/climatetimeinthe00crol>, 1875.
- Dangendorf, S., Marcos, M., Wöppelmann, G., Conrad, C. P., Frederikse, T., and Riva, R.: Reassessment of 20th century global mean sea level rise, *Proceedings of the National Academy of Sciences*, 114, 5946–5951, <https://doi.org/10.1073/pnas.1616007114>, 2017.
- Dangendorf, S., Hay, C., Calafat, F. M., Marcos, M., Piecuch, C. G., Berk, K., and Jensen, J.: Persistent acceleration in global sea-level rise since the 1960s, *Nature Climate Change*, 9, 705–710, <https://doi.org/10.1038/s41558-019-0531-8>, 2019.
- Daux, V., Garcia de Cortazar-Atauri, I., Yiou, P., Chuine, I., Garnier, E., Le Roy Ladurie, E., Mestre, O., and Tardaguila, J.: An open-access database of grape harvest dates for climate research: data description and quality assessment, *Climate of the Past*, 8, 1403–1418, <https://doi.org/10.5194/cp-8-1403-2012>, 2012.
- Deacon, M.: *Scientists and the Sea, 1650–1900*, Routledge, 0 edn., <https://doi.org/10.4324/9781315243610>, 2018.
- DeConto, R. M. and Pollard, D.: Contribution of Antarctica to past and future sea-level rise, *Nature*, 531, 591–597, <https://doi.org/10.1038/nature17145>, 2016.



- 1220 Dlugokencky, E. J., Steele, L. P., Lang, P. M., and Masarie, K. A.: The growth rate and distribution of atmospheric methane, *Journal of Geophysical Research*, 99, 17 021–17 043, <https://doi.org/10.1029/94JD01245>, 1994.
- Donovan, M. K., Adam, T. C., Shantz, A. A., Speare, K. E., Munsterman, K. S., Rice, M. M., Schmitt, R. J., Holbrook, S. J., and Burkepile, D. E.: Nitrogen pollution interacts with heat stress to increase coral bleaching across the seascape, *Proceedings of the National Academy of Sciences*, 117, 5351–5357, <https://doi.org/10.1073/pnas.1915395117>, 2020.
- 1225 Dore, J. E., Lukas, R., Sadler, D. W., Church, M. J., and Karl, D. M.: Physical and biogeochemical modulation of ocean acidification in the central North Pacific, *Proceedings of the National Academy of Sciences*, 106, 12 235–12 240, <https://doi.org/10.1073/pnas.0906044106>, 2009.
- Douglas, B. C.: Global sea level rise, *Journal of Geophysical Research: Oceans*, 96, 6981–6992, <https://doi.org/10.1029/91JC00064>, 1991.
- 1230 Durack, P., Gleckler, P., Purkey, S., Johnson, G., Lyman, J., and Boyer, T. P.: Ocean Warming: From the Surface to the Deep in Observations and Models, *Oceanography*, 31, 41–51, <https://doi.org/10.5670/oceanog.2018.227>, 2018.
- Durre, I., Vose, R. S., and Wuertz, D. B.: Overview of the Integrated Global Radiosonde Archive, *Journal of Climate*, 19, 53–68, <https://doi.org/10.1175/JCLI3594.1>, 2006.
- Dussailant, I., Hugonnet, R., Huss, M., Berthier, E., Bannwart, J., Paul, F., and Zemp, M.: Annual mass change of the world’s glaciers from 1976 to 2024 by temporal downscaling of satellite data with in situ observations, *Earth System Science Data*, 17, 1977–2006, <https://doi.org/10.5194/essd-17-1977-2025>, 2025.
- 1235 Eakin, C. M., Sweatman, H. P. A., and Brainard, R. E.: The 2014–2017 global-scale coral bleaching event: insights and impacts, *Coral Reefs*, 38, 539–545, <https://doi.org/10.1007/s00338-019-01844-2>, 2019.
- Eddy, J. A.: The Maunder Minimum, *Science*, 192, 1189–1202, <https://doi.org/10.1126/science.192.4245.1189>, 1976.
- 1240 Edwards, P. N.: A vast machine: computer models, climate data, and the politics of global warming, *Infrastructures series*, The MIT Press, Cambridge, MA, 2010.
- Edwards, T. L., Brandon, M. A., Durand, G., Edwards, N. R., Golledge, N. R., Holden, P. B., Nias, I. J., Payne, A. J., Ritz, C., and Wernecke, A.: Revisiting Antarctic ice loss due to marine ice-cliff instability, *Nature*, 566, 58–64, <https://doi.org/10.1038/s41586-019-0901-4>, 2019.
- 1245 Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R., Goelzer, H., Seroussi, H., Jourdain, N. C., Slater, D. A., Turner, F. E., Smith, C. J., McKenna, C. M., Simon, E., Abe-Ouchi, A., Gregory, J. M., Larour, E., Lipscomb, W. H., Payne, A. J., Shepherd, A., Agosta, C., Alexander, P., Albrecht, T., Anderson, B., Asay-Davis, X., Aschwanden, A., Barthel, A., Bliss, A., Calov, R., Chambers, C., Champollion, N., Choi, Y., Cullather, R., Cuzzone, J., Dumas, C., Felikson, D., Fettweis, X., Fujita, K., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huss, M., Huybrechts, P., Immerzeel, W., Kleiner, T., Kraaijenbrink, P., Le Clec’h, S., Lee, V., Leguy, G. R., Little, C. M., Lowry, D. P., Malles, J.-H., Martin, D. F., Maussion, F., Morlighem, M., O’Neill, J. F., Nias, I., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Radić, V., Reese, R., Rounce, D. R., Rückamp, M., Sakai, A., Shafer, C., Schlegel, N.-J., Shannon, S., Smith, R. S., Straneo, F., Sun, S., Tarasov, L., Trusel, L. D., Van Breedam, J., Van De Wal, R., Van Den Broeke, M., Winkelmann, R., Zekollari, H., Zhao, C., Zhang, T., and Zwinger, T.: Projected land ice contributions to
- 1250 twenty-first-century sea level rise, *Nature*, 593, 74–82, <https://doi.org/10.1038/s41586-021-03302-y>, 2021.
- Ekman, M.: The world’s longest continued series of sea level observations, pure and applied geophysics, 127, 73–77, <https://doi.org/10.1007/BF00878691>, 1988.



- Emiliani, C.: Pleistocene Temperatures, *The Journal of Geology*, 63, 538–578, <https://www.jstor.org/stable/30080906>, 1955.
- Estilow, T. W., Young, A. H., and Robinson, D. A.: A long-term Northern Hemisphere snow cover extent data record for
 1260 climate studies and monitoring, *Earth System Science Data*, 7, 137–142, <https://doi.org/10.5194/essd-7-137-2015>, 2015.
- Etheridge, D. M., Steele, L. P., Langenfelds, R. L., Francey, R. J., Barnola, J.-M., and Morgan, V. I.: Natural and anthropogenic changes in atmospheric CO₂ over the last 1000 years from air in Antarctic ice and firn, *Journal of Geophysical Research: Atmospheres*, 101, 4115–4128, <https://doi.org/10.1029/95JD03410>, 1996.
- Etheridge, D. M., Steele, L. P., Francey, R. J., and Langenfelds, R. L.: Atmospheric methane between 1000 A.D. and
 1265 present: Evidence of anthropogenic emissions and climatic variability, *Journal of Geophysical Research: Atmospheres*, 103, 15 979–15 993, <https://doi.org/10.1029/98JD00923>, 1998.
- Eyring, V., Gillett, N. P., Achuta Rao, K. M., Barimalala, R., Barreiro Parrillo, M., Bellouin, N., Cassou, C., Durack, P. J., Kosaka, Y., McGregor, S., Min, S., Morgenstern, O., and Sun, Y.: Human influence on the climate system, in: *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*, edited by Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., pp. 423–552, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, <https://doi.org/10.1017/9781009157896.005>, 2021.
- Fairbanks, R. G.: A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event
 1275 and deep-ocean circulation, *Nature*, 342, 637–642, <https://doi.org/10.1038/342637a0>, 1989.
- Fleming, J. R.: Joseph Fourier, the ‘greenhouse effect’, and the quest for a universal theory of terrestrial temperatures, *Endeavour*, 23, 72–75, [https://doi.org/10.1016/S0160-9327\(99\)01210-7](https://doi.org/10.1016/S0160-9327(99)01210-7), 1999.
- Fleming, J. R.: *The Callendar Effect: The Life and Work of Guy Stewart Callendar (1898–1964), the Scientist Who Established the Carbon Dioxide Theory of Climate Change*, SpringerLink Bücher, American Meteorological Society, Boston, MA,
 1280 <https://doi.org/10.1007/978-1-935704-04-1>, 2007.
- Fleming, J. R.: Historical perspectives on climate change, Oxford scholarship online, Oxford University Press, New York, <https://doi.org/10.1093/oso/9780195078701.001.0001>, 2020.
- Folland, C. K. and Parker, D. E.: Correction of instrumental biases in historical sea surface temperature data, *Quarterly Journal of the Royal Meteorological Society*, 121, 319–367, <https://doi.org/10.1002/qj.49712152206>, 1995.
- 1285 Foote, E. N.: Circumstances affecting the heat of the sun’s rays, *The American Journal of Science and Arts*, 22, 382–383, 1856.
- Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Hall, B., Hauser, M., Ribes, A., Rosen, D., Gillett, N. P., Palmer, M. D., Rogelj, J., von Schuckmann, K., Trewin, B., Allen, M., Andrew, R., Betts, R. A., Borger, A., Boyer, T., Broersma, J. A., Buontempo, C., Burgess, S., Cagnazzo, C., Cheng, L., Friedlingstein, P., Gettelman, A., Gütschow, J.,
 1290 Ishii, M., Jenkins, S., Lan, X., Morice, C., Mühle, J., Kadow, C., Kennedy, J., Killick, R. E., Krummel, P. B., Minx, J. C., Myhre, G., Naik, V., Peters, G. P., Pirani, A., Pongratz, J., Schleussner, C.-F., Seneviratne, S. I., Szopa, S., Thorne, P., Kovilakam, M. V. M., Majamäki, E., Jalkanen, J.-P., van Marle, M., Hoesly, R. M., Rohde, R., Schumacher, D., van der Werf, G., Vose, R., Zickfeld, K., Zhang, X., Masson-Delmotte, V., and Zhai, P.: Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence, *Earth System Science Data*, 16, 2625–2658, <https://doi.org/10.5194/essd-16-2625-2024>, 2024.



- Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Cassou, C., Hauser, M., Hausfather, Z., Lee, J.-Y., Palmer, M. D., von Schuckmann, K., Slangen, A. B. A., Szopa, S., Trewin, B., Yun, J., Gillett, N. P., Jenkins, S., Matthews, H. D., Raghavan, K., Ribes, A., Rogelj, J., Rosen, D., Zhang, X., Allen, M., Aleluia Reis, L., Andrew, R. M., Betts, R. A., Borger, A., Broersma, J. A., Burgess, S. N., Cheng, L., Friedlingstein, P., Domingues, C. M., Gambarini, M., Gasser, T., Gütschow, J., Ishii, M., Kadow, C., Kennedy, J., Killick, R. E., Krummel, P. B., Liné, A., Monselesan, D. P., Morice, C., Mühle, J., Naik, V., Peters, G. P., Pirani, A., Pongratz, J., Minx, J. C., Rigby, M., Rohde, R., Savita, A., Seneviratne, S. I., Thorne, P., Wells, C., Western, L. M., van der Werf, G. R., Wijffels, S. E., Masson-Delmotte, V., and Zhai, P.: Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence, *Earth System Science Data*, 17, 2641–2680, <https://doi.org/10.5194/essd-17-2641-2025>, 2025.
- 1300 Foster, G. L.: Seawater pH, pCO₂ and [CO₂] variations in the Caribbean Sea over the last 130 kyr: A boron isotope and B/Ca study of planktic foraminifera, *Earth and Planetary Science Letters*, 271, 254–266, <https://doi.org/10.1016/j.epsl.2008.04.015>, 2008.
- Fourier, J.-B. J.: Mémoire sur les températures du globe terrestre et des espaces planétaires, *Mémoires de l'Académie Royale des Sciences de l'Institut de France*, 7, 570–604, 1827.
- 1310 Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A., and Yu, Y.: Ocean, cryosphere and sea level change, in: *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*, edited by Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K.,
- 1315 Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., pp. 1211–1362, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, <https://doi.org/10.1017/9781009157896.011>, 2021.
- Free, M., Seidel, D. J., Angell, J. K., Lanzante, J., Durre, I., and Peterson, T. C.: Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC): A new data set of large-area anomaly time series, *Journal of Geophysical Research: Atmospheres*, 110, 2005JD006169, <https://doi.org/10.1029/2005JD006169>, 2005.
- 1320 Friedman, R. M.: *Appropriating the weather: Vilhelm Bjerknes and the construction of a modern meteorology*, Cornell University Press, Ithaca, <https://doi.org/10.7591/9781501731105>, 1993.
- Garner, A. J., Weiss, J. L., Parris, A., Kopp, R. E., Horton, R. M., Overpeck, J. T., and Horton, B. P.: Evolution of 21st Century Sea Level Rise Projections, *Earth's Future*, 6, 1603–1615, <https://doi.org/10.1029/2018EF000991>, 2018.
- GlaMBIE Team: Community estimate of global glacier mass changes from 2000 to 2023, *Nature*, 639, 382–388, <https://doi.org/10.1038/s41586-024-08545-z>, 2025.
- 1325 Gornitz, V., Lebedeff, S., and Hansen, J.: Global Sea Level Trend in the Past Century, *Science*, 215, 1611–1614, <https://doi.org/10.1126/science.215.4540.1611>, 1982.
- Gouretski, V. and Reseghetti, F.: On depth and temperature biases in bathythermograph data: Development of a new correction scheme based on analysis of a global ocean database, *Deep Sea Research Part I: Oceanographic Research Papers*, 57, 812–833, <https://doi.org/10.1016/j.dsr.2010.03.011>, 2010.
- 1330 Grant, L., Vanderkelen, I., Gudmundsson, L., Tan, Z., Perroud, M., Stepanenko, V. M., Debolskiy, A. V., Droppers, B., Janssen, A. B. G., Woolway, R. I., Choulga, M., Balsamo, G., Kirillin, G., Schewe, J., Zhao, F., del Valle, I. V., Golub,



- M., Pierson, D., Marcé, R., Seneviratne, S. I., and Thiery, W.: Attribution of global lake systems change to anthropogenic forcing, *Nature Geoscience*, 14, 849–854, <https://doi.org/10.1038/s41561-021-00833-x>, 2021.
- 1335 Greene, M. T.: Alfred Wegener, Johns Hopkins University Press, <https://doi.org/10.1353/book.42523>, 2018.
- Gulev, S. K., Thorne, P. W., Ahn, J., Dentener, F. J., Domingues, C. M., Gerland, S., Gong, D., Kaufman, D. S., Nnamchi, H. C., Quaas, J., Rivera, J. A., Sathyendranath, S., Smith, S. L., Trewin, B., von Schuckmann, K., and Vose, R. S.: Changing state of the climate system, in: *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*, edited by Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., pp. 287–422, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, <https://doi.org/10.1017/9781009157896.004>, 2021.
- 1340 Hansen, J. and Lebedeff, S.: Global trends of measured surface air temperature, *Journal of Geophysical Research: Atmospheres*, 92, 13 345–13 372, <https://doi.org/10.1029/JD092iD11p13345>, 1987.
- 1345 Hansen, J., Johnson, D., Lacis, A., Lebedeff, S., Lee, P., Rind, D., and Russell, G.: Climate Impact of Increasing Atmospheric Carbon Dioxide, *Science*, 213, 957–966, <https://doi.org/10.1126/science.213.4511.957>, 1981.
- Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedeff, S., Ruedy, R., Russell, G., and Stone, P.: Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model, *Journal of Geophysical Research: Atmospheres*, 93, 9341–9364, <https://doi.org/10.1029/JD093iD08p09341>, 1988.
- 1350 Hansen, J., Ruedy, R., Sato, M., and Lo, K.: Global Surface Temperature Change, *Reviews of Geophysics*, 48, <https://doi.org/10.1029/2010RG000345>, 2010.
- Hansen, J. E. and Lacis, A. A.: Sun and dust versus greenhouse gases: an assessment of their relative roles in global climate change, *Nature*, 346, 713–719, <https://doi.org/10.1038/346713a0>, 1990.
- Hausfather, Z., Menne, M. J., Williams, C. N., Masters, T., Broberg, R., and Jones, D.: Quantifying the effect of urbanization on U.S. Historical Climatology Network temperature records, *Journal of Geophysical Research: Atmospheres*, 118, 481–494, <https://doi.org/10.1029/2012JD018509>, 2013.
- 1355 Hausfather, Z., Cowtan, K., Menne, M. J., and Williams, C. N.: Evaluating the impact of U.S. Historical Climatology Network homogenization using the U.S. Climate Reference Network, *Geophysical Research Letters*, 43, 1695–1701, <https://doi.org/10.1002/2015GL067640>, 2016.
- 1360 Hawkins, E. and Jones, P. D.: On increasing global temperatures: 75 years after Callendar, *Quarterly Journal of the Royal Meteorological Society*, 139, 1961–1963, <https://doi.org/10.1002/qj.2178>, 2013.
- Hay, C. C., Morrow, E., Kopp, R. E., and Mitrovica, J. X.: Probabilistic reanalysis of twentieth-century sea-level rise, *Nature*, 517, 481–484, <https://doi.org/10.1038/nature14093>, 2015.
- Hays, J. D., Imbrie, J., and Shackleton, N. J.: Variations in the Earth’s Orbit: Pacemaker of the Ice Ages, *Science*, 194, 1121–1132, <https://doi.org/10.1126/science.194.4270.1121>, 1976.
- 1365 Helfrich, S. R., McNamara, D., Ramsay, B. H., Baldwin, T., and Kasheta, T.: Enhancements to, and forthcoming developments in the Interactive Multisensor Snow and Ice Mapping System (IMS), *Hydrological Processes*, 21, 1576–1586, <https://doi.org/10.1002/hyp.6720>, 2007.
- Hemming, N. G. and Hanson, G. N.: Boron isotopic composition and concentration in modern marine carbonates, *Geochimica et Cosmochimica Acta*, 56, 537–543, [https://doi.org/10.1016/0016-7037\(92\)90151-8](https://doi.org/10.1016/0016-7037(92)90151-8), 1992.
- 1370



- Hibbert, F., Williams, F., Fallon, S., and Rohling, E.: A database of biological and geomorphological sea-level markers from the Last Glacial Maximum to present, *Scientific Data*, 5, 180 088, <https://doi.org/10.1038/sdata.2018.88>, 2018.
- Hirahara, S., Ishii, M., and Fukuda, Y.: Centennial-Scale Sea Surface Temperature Analysis and Its Uncertainty, *Journal of Climate*, 27, 57–75, <https://doi.org/10.1175/JCLI-D-12-00837.1>, 2014.
- 1375 Ho, H. L.: The Legal Concept of Evidence, in: *The Stanford Encyclopedia of Philosophy*, edited by Zalta, E. N., Metaphysics Research Lab, Stanford University, winter 2021 edn., <https://plato.stanford.edu/archives/win2021/entries/evidence-legal/>, 2021.
- Hoinka, K. P.: The tropopause: discovery, definition and demarcation, *Meteorologische Zeitschrift*, 6, 281–303, <https://doi.org/10.1127/metz/6/1997/281>, 1997.
- 1380 Howe, J. P.: Behind the curve: science and the politics of global warming, Weyerhaeuser environmental books, University of Washington Press, Seattle, <https://doi.org/10.1515/9780295805092>, 2014.
- Hu, S., Guo, L., Zhu, C., Xie, W., He, Q., and Lu, Z.: Centennial mean and maximal sea level changes at Wusong in the Yangtze Estuary, *Science China Earth Sciences*, 69, 1760–1771, <https://doi.org/10.1007/s11430-025-1833-9>, 2026.
- Huang, B., Yin, X., Boyer, T., Liu, C., Menne, M., Rao, Y. D., Smith, T., Vose, R., and Zhang, H.-M.: Extended Reconstructed Sea Surface Temperature, Version 6 (ERSSTv6). Part I: An Artificial Neural Network Approach, *Journal of Climate*, 38, 1105–1121, <https://doi.org/10.1175/JCLI-D-23-0707.1>, 2025.
- 1385 Hughes, T.: Is the West Antarctic Ice Sheet disintegrating?, *Journal of Geophysical Research* (1896-1977), 78, 7884–7910, <https://doi.org/10.1029/JC078i033p07884>, 1973.
- Hughes, T. P., Kerry, J. T., Álvarez Noriega, M., Álvarez Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., 1390 Beger, M., Bellwood, D. R., Berkelmans, R., Bridge, T. C., Butler, I. R., Byrne, M., Cantin, N. E., Comeau, S., Connolly, S. R., Cumming, G. S., Dalton, S. J., Diaz-Pulido, G., Eakin, C. M., Figueira, W. F., Gilmour, J. P., Harrison, H. B., Heron, S. F., Hoey, A. S., Hobbs, J.-P. A., Hoogenboom, M. O., Kennedy, E. V., Kuo, C.-y., Lough, J. M., Lowe, R. J., Liu, G., McCulloch, M. T., Malcolm, H. A., McWilliam, M. J., Pandolfi, J. M., Pears, R. J., Pratchett, M. S., Schoepf, V., Simpson, T., Skirving, W. J., Sommer, B., Torda, G., Wachenfeld, D. R., Willis, B. L., and Wilson, S. K.: Global warming 1395 and recurrent mass bleaching of corals, *Nature*, 543, 373–377, <https://doi.org/10.1038/nature21707>, 2017.
- Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., and Kääb, A.: Accelerated global glacier mass loss in the early twenty-first century, *Nature*, 592, 726–731, <https://doi.org/10.1038/s41586-021-03436-z>, 2021.
- IMBIE Team: Mass balance of the Antarctic Ice Sheet from 1992 to 2017, *Nature*, 558, 219–222, 1400 <https://doi.org/10.1038/s41586-018-0179-y>, 2018.
- Inkpen, D.: Of Ice and Men: The Evolving Role of the Camera in Twentieth-Century Glacier Study, *Environmental History*, 27, 547–560, <https://doi.org/10.1086/719791>, 2022.
- Inkpen, D.: Capturing glaciers: a history of repeat photography and global warming, Weyerhaeuser environmental books, University of Washington Press, Seattle, 2023.
- 1405 Inkpen, D. K.: Frozen icons: The science and politics of repeat glacier photographs, 1887–2010, Ph.D. dissertation, Harvard University, 2018.
- International Coral Reef Initiative: The Fourth Global Coral Bleaching Event, <https://icriforum.org/4gbe/>, 2025.



- International Court of Justice: Obligations of states in respect of climate change (advisory opinion), <https://www.icj-cij.org/case/187>, 2025.
- 1410 IPCC: Climate change: The IPCC scientific assessment, Cambridge University Press, Cambridge, UK, 1990.
 IPCC: Climate change 1995: The science of climate change, Cambridge University Press, Cambridge, UK, 1995.
 IPCC: Climate Change 2001: The Scientific Basis, Cambridge University Press, Cambridge, <https://www.ipcc.ch/report/ar3/wg1/>, 2001.
- 1415 IPCC: Climate Change 2007: The Physical Science Basis, Cambridge University Press, Cambridge, <https://www.ipcc.ch/report/ar4/wg1/>, 2007.
- IPCC: Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, <https://doi.org/10.1017/CBO9781107415324>, 2013.
- 1420 IPCC: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 1 edn., <https://doi.org/10.1017/9781009157896>, 2021.
- IPCC: Oceans and Coastal Ecosystems and Their Services, in: Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Intergovernmental Panel on Climate Change (IPCC), pp. 379–550, Cambridge University Press, Cambridge, <https://doi.org/10.1017/9781009325844.005>, 2023.
- 1425 Irion, R.: “Urban Heat Island” debate cools down, <https://www.science.org/content/article/urban-heat-island-debate-cools-down>, 1999.
- Jackson, R.: Eunice Foote, John Tyndall and a question of priority, Notes and Records: the Royal Society Journal of the History of Science, 74, 105–118, <https://doi.org/10.1098/rsnr.2018.0066>, 2020.
- 1430 Jayne, S. R., Roemmich, D., Zilberman, N., Riser, S. C., and Johnson, K. S.: The Argo Program: Present and Future, Oceanography, 30, 18–28, <https://doi.org/10.5670/oceanog.2017.213>, 2017.
- Jones, P. D., Wigley, T. M. L., and Wright, P. B.: Global temperature variations between 1861 and 1984, Nature, 322, 430–434, <https://doi.org/10.1038/322430a0>, 1986.
- 1435 Jones, P. D., Groisman, P. Y., Coughlan, M., Plummer, N., Wang, W.-C., and Karl, T. R.: Assessment of urbanization effects in time series of surface air temperature over land, Nature, 347, 169–172, <https://doi.org/10.1038/347169a0>, 1990.
- Karl, D. M. and Lukas, R.: The Hawaii Ocean Time-series (HOT) program: Background, rationale and field implementation, Deep Sea Research Part II: Topical Studies in Oceanography, 43, 129–156, [https://doi.org/10.1016/0967-0645\(96\)00005-7](https://doi.org/10.1016/0967-0645(96)00005-7), 1996.
- 1440 Karoly, D. J.: Northern hemisphere temperature trends: A possible greenhouse gas effect?, Geophysical Research Letters, 16, 465–468, <https://doi.org/10.1029/GL016i005p00465>, 1989.
- Keeling, C. D.: The Concentration and Isotopic Abundances of Carbon Dioxide in the Atmosphere, Tellus, 12, 200–203, <https://doi.org/10.1111/j.2153-3490.1960.tb01300.x>, 1960.
- Kemp, A. C., Horton, B. P., Donnelly, J. P., Mann, M. E., Vermeer, M., and Rahmstorf, S.: Climate related sea-level variations over the past two millennia, Proceedings of the National Academy of Sciences, 108, 11017–11022, <https://doi.org/10.1073/pnas.1015619108>, 2011.
- 1445



- Kennedy, J. J.: A review of uncertainty in in situ measurements and data sets of sea surface temperature: IN SITU SST UNCERTAINTY, *Reviews of Geophysics*, 52, 1–32, <https://doi.org/10.1002/2013RG000434>, 2014.
- Kennedy, J. J., Rayner, N. A., Atkinson, C. P., and Killick, R. E.: An Ensemble Data Set of Sea Surface Temperature Change From 1850: The Met Office Hadley Centre HadSST.4.0.0.0 Data Set, *Journal of Geophysical Research: Atmospheres*, 124, 7719–7763, <https://doi.org/10.1029/2018JD029867>, 2019.
- Kopp, G. and Lean, J. L.: A new, lower value of total solar irradiance: Evidence and climate significance, *Geophysical Research Letters*, 38, <https://doi.org/10.1029/2010GL045777>, 2011.
- Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., Hay, C. C., Mitrovica, J. X., Morrow, E. D., and Rahmstorf, S.: Temperature-driven global sea-level variability in the Common Era, *Proceedings of the National Academy of Sciences*, 113, E1434–E1441, <https://doi.org/10.1073/pnas.1517056113>, 2016.
- Krabill, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., and Yungel, J.: Rapid Thinning of Parts of the Southern Greenland Ice Sheet, *Science*, 283, 1522–1524, <https://doi.org/10.1126/science.283.5407.1522>, 1999.
- Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., and Yungel, J.: Greenland Ice Sheet: High-Elevation Balance and Peripheral Thinning, *Science*, 289, 428–430, <https://doi.org/10.1126/science.289.5478.428>, 2000.
- Labbé, T., Pfister, C., Brönnimann, S., Rousseau, D., Franke, J., and Bois, B.: The longest homogeneous series of grape harvest dates, Beaune 1354–2018, and its significance for the understanding of past and present climate, *Climate of the Past*, 15, 1485–1501, <https://doi.org/10.5194/cp-15-1485-2019>, 2019.
- Lachenbruch, A. H. and Marshall, B. V.: Changing Climate: Geothermal Evidence from Permafrost in the Alaskan Arctic, *Science*, 234, 689–696, <https://doi.org/10.1126/science.234.4777.689>, 1986.
- Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambridge, M.: Sea level and global ice volumes from the Last Glacial Maximum to the Holocene, *Proceedings of the National Academy of Sciences*, 111, 15 296–15 303, <https://doi.org/10.1073/pnas.1411762111>, 2014.
- Langenfelds, R. L., Fraser, P. J., Francey, R. J., Steele, L. P., Porter, L. W., and Allison, C. E.: The Cape Grim Air Archive: the first seventeen years, 1978–1995, in: *Baseline Atmospheric Program Australia*, edited by Francey, R. J., Dick, A. L., and Derek, N., pp. 53–70, Bureau of Meteorology and CSIRO Division of Atmospheric Research, Melbourne, <http://hdl.handle.net/102.100.100/230058?index=1>, 1996.
- Lau, S. C. Y., Wilson, N. G., Golledge, N. R., Naish, T. R., Watts, P. C., Silva, C. N. S., Cooke, I. R., Allcock, A. L., Mark, F. C., Linse, K., and Strugnell, J. M.: Genomic evidence for West Antarctic Ice Sheet collapse during the Last Interglacial, *Science*, 382, 1384–1389, <https://doi.org/10.1126/science.ade0664>, 2023.
- Laudan, L.: William Whewell on the Consilience of Inductions, *The Monist*, 55, 368–391, <https://www.jstor.org/stable/27902225>, 1971.
- Lauvset, S. K., Gruber, N., Landschützer, P., Olsen, A., and Tjiputra, J.: Trends and drivers in global surface ocean pH over the past 3 decades, *Biogeosciences*, 12, 1285–1298, <https://doi.org/10.5194/bg-12-1285-2015>, 2015.
- Le Treut, H., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson, T., and Prather, M.: Historical overview of climate change science, in: *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*, edited by Solomon,



- S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., pp. 93–127, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, <https://www.ipcc.ch/report/ar4/wg1/historical-overview-of-climate-change-science/>, 2007.
- Lean, J., Beer, J., and Bradley, R.: Reconstruction of solar irradiance since 1610: Implications for climate change, *Geophysical Research Letters*, 22, 3195–3198, <https://doi.org/10.1029/95GL03093>, 1995.
- Lenssen, N., Schmidt, G. A., Hendrickson, M., Jacobs, P., Menne, M. J., and Ruedy, R.: A NASA GIS-
 1490 TEMPv4 Observational Uncertainty Ensemble, *Journal of Geophysical Research: Atmospheres*, 129, e2023JD040179, <https://doi.org/10.1029/2023JD040179>, 2024.
- Levitus, S., Antonov, J. I., Boyer, T. P., and Stephens, C.: Warming of the World Ocean, *Science*, 287, 2225–2229, <https://doi.org/10.1126/science.287.5461.2225>, 2000.
- Lin, Y., Kopp, R. E., Xiong, H., Hibbert, F. D., Zheng, Z., Yu, F., Kumar, P., Dangendorf, S., Yi, H., and Zhang, Y.: Modern
 1495 sea-level rise breaks 4,000-year stability in southeastern China, *Nature*, 646, 856–864, <https://doi.org/10.1038/s41586-025-09600-z>, 2025.
- Liu, Y., Li, J., Fasullo, J., and Galloway, D. L.: Land subsidence contributions to relative sea level rise at tide gauge Galveston Pier 21, Texas, *Scientific Reports*, 10, 17 905, <https://doi.org/10.1038/s41598-020-74696-4>, 2020.
- Lockwood, M. and Fröhlich, C.: Recent oppositely directed trends in solar climate forcings and the global mean surface
 1500 air temperature, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 463, 2447–2460, <https://doi.org/10.1098/rspa.2007.1880>, 2007.
- Lockwood, M. and Fröhlich, C.: Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature. II. Different reconstructions of the total solar irradiance variation and dependence on response time scale, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 464, 1367–1385, <https://doi.org/10.1098/rspa.2007.0347>, 2008.
- 1505 Loeb, N. G., Johnson, G. C., Thorsen, T. J., Lyman, J. M., Rose, F. G., and Kato, S.: Satellite and Ocean Data Reveal Marked Increase in Earth’s Heating Rate, *Geophysical Research Letters*, 48, e2021GL093047, <https://doi.org/10.1029/2021GL093047>, 2021.
- Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K., and Stocker, T. F.: High-resolution carbon dioxide concentration record 650,000–800,000 years before present, *Nature*, 453, 379–382, <https://doi.org/10.1038/nature06949>, 2008.
- Macfarlane, R. A.: Wild Laboratories of Climate Change: Plants, Phenology, and Global Warming, 1955–1980, *Journal of the History of Biology*, 54, 311–340, <https://doi.org/10.1007/s10739-021-09643-8>, 2021.
- MACFARLANE, R. A.: The Many Pollutant Identities of Carbon Dioxide: Global Climate Monitoring and Air Pollution Research in New Zealand, 1968–1975, *Environment and History*, 30, 131–155, <https://doi.org/10.3197/096734022X16552219786627>, 2024.
- 1515 MacFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., van Ommen, T., Smith, A., and Elkins, J.: Law Dome CO₂, CH₄ and N₂O ice core records extended to 2000 years BP, *Geophysical Research Letters*, 33, <https://doi.org/10.1029/2006GL026152>, 2006.
- 1520 Magnuson, J. J., Robertson, D. M., Benson, B. J., Wynne, R. H., Livingstone, D. M., Arai, T., Assel, R. A., Barry, R. G., Card, V., Kuusisto, E., Granin, N. G., Prowse, T. D., Stewart, K. M., and Vuglinski, V. S.: Historical Trends in Lake



- and River Ice Cover in the Northern Hemisphere, *Science*, 289, 1743–1746, <https://doi.org/10.1126/science.289.5485.1743>, 2000.
- Malles, J.-H. and Marzeion, B.: Twentieth century global glacier mass change: an ensemble-based model reconstruction, *The Cryosphere*, 15, 3135–3157, <https://doi.org/10.5194/tc-15-3135-2021>, 2021.
- 1525 Manabe, S. and Wetherald, R. T.: Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity, *Journal of the Atmospheric Sciences*, 24, 241–259, [https://doi.org/10.1175/1520-0469\(1967\)024<0241:TEOTAW>2.0.CO;2](https://doi.org/10.1175/1520-0469(1967)024<0241:TEOTAW>2.0.CO;2), 1967.
- Manley, G.: Central England temperatures: Monthly means 1659 to 1973, *Quarterly Journal of the Royal Meteorological Society*, 100, 389–405, <https://doi.org/10.1002/qj.49710042511>, 1974.
- 1530 Masarie, K. A. and Tans, P. P.: Extension and integration of atmospheric carbon dioxide data into a globally consistent measurement record, *Journal of Geophysical Research: Atmospheres*, 100, 11 593–11 610, <https://doi.org/10.1029/95JD00859>, 1995.
- Maunder, E. W.: A prolonged sunspot minimum, *Knowledge-creation Diffusion Utilization*, 17, 173–176, <https://books.google.com/books?id=vEjnAAAAMAAJ&pg=PA173>, 1894.
- 1535 McConnell, A.: No sea too deep: the history of oceanographic instruments, Hilger, Bristol, 1982.
- Mears, C. A. and Wentz, F. J.: The Effect of Diurnal Correction on Satellite-Derived Lower Tropospheric Temperature, *Science*, 309, 1548–1551, <https://doi.org/10.1126/science.1114772>, 2005.
- Mercer, J. H.: *Glaciers of the Antarctic*, American Geographical Society, New York, 1967.
- 1540 Mercer, J. H.: Antarctic ice and Sangamon sea level, in: *Commission of Snow and Ice: Reports and Discussions*, General Assembly of Bern, 25 September – 7 October 1967, IAHS publication, pp. 217–225, International Association of Scientific Hydrology, Gentbrugge, Belgium, <https://iahs.info/uploads/dms/079020.pdf>, 1968.
- Mercer, J. H.: West Antarctic ice sheet and CO₂ greenhouse effect: a threat of disaster, *Nature*, 271, 321–325, <https://doi.org/10.1038/271321a0>, 1978.
- 1545 Middleton, W. E. K.: *A History of the Thermometer and Its Use in Meteorology*, Johns Hopkins University Press, 1966.
- Milanković, M.: *Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem*, Posebna izdanja (special publication), Königlich Serbische Akademie, Belgrade, 1941.
- Miller, G. H., Geirsdóttir, A., Zhong, Y., Larsen, D. J., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Refsnider, K. A., Lehman, S. J., Southon, J. R., Anderson, C., Björnsson, H., and Thordarson, T.: Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks, *Geophysical Research Letters*, 39, <https://doi.org/10.1029/2011GL050168>, 2012.
- 1550 Mitchell, J. F. B., Johns, T. C., Gregory, J. M., and Tett, S. F. B.: Climate response to increasing levels of greenhouse gases and sulphate aerosols, *Nature*, 376, 501–504, <https://doi.org/10.1038/376501a0>, 1995.
- Mitrovica, J. X. and Milne, G. A.: On post-glacial sea level: I. General theory, *Geophysical Journal International*, 154, 253–267, <https://doi.org/10.1046/j.1365-246X.2003.01942.x>, 2003.
- 1555 Mok, H. Y. and Lui, W. H.: Story of a bolt, <https://www.hko.gov.hk/en/Observatorys-Blog/101807/Story-of-a-Bolt>, 2016.
- Molena, F.: Remarkable weather of 1911: The effect of the combustion of coal on the climate, *Popular Mechanics Magazine*, 17, 339–342, https://archive.org/details/sim_popular-mechanics_popular-mechanics_1912-03_17_3/page/339/mode/1up, 1912.



- 1560 Morice, C. P., Kennedy, J. J., Rayner, N. A., Winn, J. P., Hogan, E., Killick, R. E., Dunn, R. J. H., Osborn, T. J., Jones, P. D., and Simpson, I. R.: An Updated Assessment of Near-Surface Temperature Change From 1850: The HadCRUT5 Data Set, *Journal of Geophysical Research: Atmospheres*, 126, e2019JD032361, <https://doi.org/10.1029/2019JD032361>, 2021.
- Morlighem, M., Goldberg, D., Barnes, J. M., Bassis, J. N., Benn, D. I., Crawford, A. J., Gudmundsson, G. H., and Seroussi, H.: The West Antarctic Ice Sheet may not be vulnerable to marine ice cliff instability during the 21st century, *Science Advances*, 10, eado7794, <https://doi.org/10.1126/sciadv.ado7794>, 2024.
- 1565 Mudryk, L., Santolaria-Otín, M., Krinner, G., Ménégos, M., Derksen, C., Brutel-Vuilmet, C., Brady, M., and Essery, R.: Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble, *The Cryosphere*, 14, 2495–2514, <https://doi.org/10.5194/tc-14-2495-2020>, 2020.
- Muller, R. A., Rohde, R., Jacobsen, R., Muller, E., and Wickham, C.: A New Estimate of the Average Earth Surface Land Temperature Spanning 1753 to 2011, *Geoinformatics & Geostatistics: An Overview*, 01, <https://doi.org/10.4172/2327-4581.1000101>, 2013.
- 1570 National Research Council: *Changing Climate: Report of the Carbon Dioxide Assessment Committee*, National Academies Press, Washington, D.C., <https://doi.org/10.17226/18714>, 1983.
- Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., and Mitchum, G. T.: Climate-change-driven accelerated sea-level rise detected in the altimeter era, *Proceedings of the National Academy of Sciences*, 115, 2022–2025, <https://doi.org/10.1073/pnas.1717312115>, 2018.
- 1575 Newton, A. M. W. and Mullan, D. J.: Climate change and Northern Hemisphere lake and river ice phenology from 1931–2005, *The Cryosphere*, 15, 2211–2234, <https://doi.org/10.5194/tc-15-2211-2021>, 2021.
- Nicholls, R. J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A. T., Meyssignac, B., Hanson, S. E., Merkens, J.-L., and Fang, J.: A global analysis of subsidence, relative sea-level change and coastal flood exposure, *Nature Climate Change*, 11, 338–342, <https://doi.org/10.1038/s41558-021-00993-z>, 2021.
- 1580 NOAA: NOAA Confirms Fourth Global Coral Bleaching Event, <https://www.nesdis.noaa.gov/news/noaa-confirms-fourth-global-coral-bleaching-event>, 2025a.
- NOAA: Assessing the global climate in 2024, <https://www.ncei.noaa.gov/news/global-climate-202413>, 2025b.
- 1585 NOAA Coral Reef Watch: NOAA Coral Reef Watch Current Global Bleaching: Status Update & Data Submission, https://coralreefwatch.noaa.gov/satellite/research/coral_bleaching_report.php, 2025.
- Oerlemans, J.: Quantifying Global Warming from the Retreat of Glaciers, *Science*, 264, 243–245, <https://doi.org/10.1126/science.264.5156.243>, 1994.
- Oreskes, N.: "Laissez-tomber": Military Patronage and Women's Work in Mid-20th-Century Oceanography, *Historical Studies in the Physical and Biological Sciences*, 30, 373–392, <https://doi.org/10.2307/27757836>, 2000.
- 1590 Oreskes, N.: *Science on a Mission: How Military Funding Shaped What We Do and Don't Know about the Ocean*, University of Chicago Press, <https://doi.org/10.7208/chicago/9780226732411.001.0001>, 2021.
- Oreskes, N., Shrader-Frechette, K., and Belitz, K.: Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences, *Science*, 263, 641–646, <https://doi.org/10.1126/science.263.5147.641>, 1994.
- 1595 Oreskes, N., Lanier-Christensen, C., Conway, H., and Macfarlane, R. A.: Climate change and the Clean Air Act of 1970 Part I: The scientific basis, *Ecology Law Quarterly*, 50, 811–890, <https://doi.org/10.15779/Z38DV1CP99>, 2023.



- Osterkamp, T. E. and Romanovsky, V. E.: Evidence for warming and thawing of discontinuous permafrost in Alaska, *Permafrost and Periglacial Processes*, 10, 17–37, [https://doi.org/10.1002/\(SICI\)1099-1530\(199901/03\)10:1<17::AID-PPP303>3.0.CO;2-4](https://doi.org/10.1002/(SICI)1099-1530(199901/03)10:1<17::AID-PPP303>3.0.CO;2-4), 1999.
- 1600 Ootosaka, I. N., Shepherd, A., Ivins, E. R., Schlegel, N.-J., Amory, C., van den Broeke, M. R., Horwath, M., Joughin, I., King, M. D., Krinner, G., Nowicki, S., Payne, A. J., Rignot, E., Scambos, T., Simon, K. M., Smith, B. E., Sørensen, L. S., Velicogna, I., Whitehouse, P. L., A. G., Agosta, C., Ahlstrøm, A. P., Blazquez, A., Colgan, W., Engdahl, M. E., Fettweis, X., Forsberg, R., Gallée, H., Gardner, A., Gilbert, L., Gourmelen, N., Groh, A., Gunter, B. C., Harig, C., Helm, V., Khan, S. A., Kittel, C., Konrad, H., Langen, P. L., Lecavalier, B. S., Liang, C.-C., Loomis, B. D., McMillan, M., Melini, D., Mernild, S. H., Mottram, R., Mouginit, J., Nilsson, J., Noël, B., Pattie, M. E., Peltier, W. R., Pie, N., Roca, M., Sasgen, I., Save, H. V., Seo, K.-W., Scheuchl, B., Schrama, E. J. O., Schröder, L., Simonsen, S. B., Slater, T., Spada, G., Sutterley, T. C., Vishwakarma, B. D., van Wessem, J. M., Wiese, D., van der Wal, W., and Wouters, B.: Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020, *Earth System Science Data*, 15, 1597–1616, <https://doi.org/10.5194/essd-15-1597-2023>, 2023.
- 1605 Parker, D. E.: Effects of changing exposure of thermometers at land stations, *International Journal of Climatology*, 14, 1–31, <https://doi.org/10.1002/joc.3370140102>, 1994.
- Parker, D. E.: Large-scale warming is not urban, *Nature*, 432, 290–290, <https://doi.org/10.1038/432290a>, 2004.
- Parker, D. E.: A Demonstration That Large-Scale Warming Is Not Urban, *Journal of Climate*, 19, 2882–2895, <https://doi.org/10.1175/JCLI3730.1>, 2006.
- 1615 Parker, D. E.: Uncertainties in early Central England temperatures, *International Journal of Climatology*, 30, 1105–1113, <https://doi.org/10.1002/joc.1967>, 2010a.
- Parker, D. E.: Urban heat island effects on estimates of observed climate change, *WIREs Climate Change*, 1, 123–133, <https://doi.org/10.1002/wcc.21>, 2010b.
- Parker, D. E., Legg, T. P., and Folland, C. K.: A new daily central England temperature series, 1772–1991, *International Journal of Climatology*, 12, 317–342, <https://doi.org/10.1002/joc.3370120402>, 1992.
- 1620 Pavlov, A. V.: Current changes of climate and permafrost in the arctic and sub-arctic of Russia, *Permafrost and Periglacial Processes*, 5, 101–110, <https://doi.org/10.1002/ppp.3430050204>, 1994.
- Peel, J. and Osofsky, H. M.: Climate change litigation: regulatory pathways to cleaner energy, no. 116 in *Cambridge studies in international and comparative law*, Cambridge University Press, Cambridge, United Kingdom, <https://doi.org/10.1017/CBO9781139565851>, 2015.
- 1625 Peltier, W. R.: GLOBAL GLACIAL ISOSTASY AND THE SURFACE OF THE ICE-AGE EARTH: The ICE-5G (VM2) Model and GRACE, *Annual Review of Earth and Planetary Sciences*, 32, 111–149, <https://doi.org/10.1146/annurev.earth.32.082503.144359>, 2004.
- Peterson, T. C., Gallo, K. P., Lawrimore, J., Owen, T. W., Huang, A., and McKittrick, D. A.: Global rural temperature trends, *Geophysical Research Letters*, 26, 329–332, <https://doi.org/10.1029/1998GL900322>, 1999.
- 1630 Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., and Stievenard, M.: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, 399, 429–436, <https://doi.org/10.1038/20859>, 1999.



- 1635 Pfeffer, W. T., Arendt, A. A., Bliss, A., Bolch, T., Cogley, J. G., Gardner, A. S., Hagen, J.-O., Hock, R., Kaser, G., Kienholz, C., Miles, E. S., Moholdt, G., Mölg, N., Paul, F., Radić, V., Rastner, P., Raup, B. H., Rich, J., Sharp, M. J., and Consortium, T. R.: The Randolph Glacier Inventory: a globally complete inventory of glaciers, *Journal of Glaciology*, 60, 537–552, <https://doi.org/10.3189/2014JoG13J176>, 2014.
- Pollard, D., DeConto, R. M., and Alley, R. B.: Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure, *Earth and Planetary Science Letters*, 412, 112–121, <https://doi.org/10.1016/j.epsl.2014.12.035>, 2015.
- 1640 Prinn, R. G., Weiss, R. F., Fraser, P. J., Simmonds, P. G., Cunnold, D. M., Alyea, F. N., O'Doherty, S., Salameh, P., Miller, B. R., Huang, J., Wang, R. H. J., Hartley, D. E., Harth, C., Steele, L. P., Sturrock, G., Midgley, P. M., and McCulloch, A.: A history of chemically and radiatively important gases in air deduced from ALE/GAGE/AGAGE, *Journal of Geophysical Research: Atmospheres*, 105, 17 751–17 792, <https://doi.org/10.1029/2000JD900141>, 2000.
- 1645 Rahmstorf, S.: A Semi-Empirical Approach to Projecting Future Sea-Level Rise, *Science*, 315, 368–370, <https://doi.org/10.1126/science.1135456>, 2007.
- Ramaswamy, V., Schwarzkopf, M. D., and Randel, W. J.: Fingerprint of ozone depletion in the spatial and temporal pattern of recent lower-stratospheric cooling, *Nature*, 382, 616–618, <https://doi.org/10.1038/382616a0>, 1996.
- Ångström, K.: Ueber die Bedeutung des Wasserdampfes und der Kohlensäure bei der Absorption der Erdatmosphäre, *Annalen der Physik*, 308, 720–732, <https://doi.org/10.1002/andp.19003081208>, 1900.
- 1650 Rasmussen, R. A. and Khalil, M. A. K.: Atmospheric methane (CH₄): Trends and seasonal cycles, *Journal of Geophysical Research: Oceans*, 86, 9826–9832, <https://doi.org/10.1029/JC086iC10p09826>, 1981.
- Rasool, S. I. and Schneider, S. H.: Atmospheric Carbon Dioxide and Aerosols: Effects of Large Increases on Global Climate, *Science*, 173, 138–141, <https://doi.org/10.1126/science.173.3992.138>, 1971.
- 1655 Revelle, R. and Suess, H. E.: Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO₂ during the Past Decades, *Tellus*, 9, 18–27, <https://doi.org/10.1111/j.2153-3490.1957.tb01849.x>, 1957.
- Reynolds, R. W., Rayner, N. A., Smith, T. M., Stokes, D. C., and Wang, W.: An Improved In Situ and Satellite SST Analysis for Climate, *Journal of Climate*, 15, 1609–1625, [https://doi.org/10.1175/1520-0442\(2002\)015<1609:AIISAS>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<1609:AIISAS>2.0.CO;2), 2002.
- RGI Consortium: Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 7, <https://doi.org/10.5067/F6JMOVY5NAVZ>, 2023.
- 1660 Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbéoch, M., Gilbert, D., Xu, J., Pouliquen, S., Thresher, A., Le Traon, P.-Y., Maze, G., Klein, B., Ravichandran, M., Grant, F., Poulain, P.-M., Suga, T., Lim, B., Sterl, A., Sutton, P., Mork, K.-A., Vélez-Belchí, P. J., Ansorge, I., King, B., Turton, J., Baringer, M., and Jayne, S. R.: Fifteen years of ocean observations with the global Argo array, *Nature Climate Change*, 6, 145–153, <https://doi.org/10.1038/nclimate2872>, 2016.
- 1665 Robinson, D. A. and Dewey, K. F.: Recent secular variations in the extent of Northern Hemisphere snow cover, *Geophysical Research Letters*, 17, 1557–1560, <https://doi.org/10.1029/GL017i010p01557>, 1990.
- Robinson, D. A., Dewey, K. F., and Heim, R. R.: Global Snow Cover Monitoring: An Update, *Bulletin of the American Meteorological Society*, 74, 1689–1696, [https://doi.org/10.1175/1520-0477\(1993\)074<1689:GSCMAU>2.0.CO;2](https://doi.org/10.1175/1520-0477(1993)074<1689:GSCMAU>2.0.CO;2), 1993.
- Robinson, D. A., Estilow, T. W., and NOAA CDR Program: NOAA climate data record (CDR) of Northern Hemisphere (NH) snow cover extent (SCE), version 1, <https://doi.org/10.7289/V5N014G9>, 2012.
- 1670 Robock, A.: Volcanic eruptions and climate, *Reviews of Geophysics*, 38, 191–219, <https://doi.org/10.1029/1998RG000054>, 2000.



- Roemmich, D. and Owens, B.: The Argo Project: Global Ocean Observations for Understanding and Prediction of Climate Variability, *Oceanography*, 13, 45–50, <https://doi.org/10.5670/oceanog.2000.33>, 2000.
- 1675 Rohling, E. J., Foster, G. L., Gernon, T. M., Grant, K. M., Heslop, D., Hibbert, F. D., Roberts, A. P., and Yu, J.: Comparison and Synthesis of Sea-Level and Deep-Sea Temperature Variations Over the Past 40 Million Years, *Reviews of Geophysics*, 60, e2022RG000775, <https://doi.org/10.1029/2022RG000775>, 2022.
- Romanovsky, V. E., Smith, S. L., and Christiansen, H. H.: Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007–2009: a synthesis, *Permafrost and Periglacial Processes*, 21, 106–116, <https://doi.org/10.1002/ppp.689>, 2010.
- 1680 Rozwadowski, H. M. and Van Keuren, D. K., eds.: The machine in Neptune’s garden: historical perspectives on technology and the marine environment, Science History Publications/USA, Sagamore Beach, MA, 2004.
- Rubino, M., Etheridge, D. M., Thornton, D. P., Howden, R., Allison, C. E., Francey, R. J., Langenfelds, R. L., Steele, L. P., Trudinger, C. M., Spencer, D. A., Curran, M. A. J., van Ommen, T. D., and Smith, A. M.: Revised records of atmospheric trace gases CO₂, CH₄, N₂O, and ¹³C-CO₂ over the last 2000 years from Law Dome, Antarctica, *Earth System Science Data*, 11, 473–492, <https://doi.org/10.5194/essd-11-473-2019>, 2019.
- 1685 Santana-Casiano, J. M., González-Dávila, M., Rueda, M.-J., Llinás, O., and González-Dávila, E.-F.: The interannual variability of oceanic CO₂ parameters in the northeast Atlantic subtropical gyre at the ESTOC site, *Global Biogeochemical Cycles*, 21, 2006GB002788, <https://doi.org/10.1029/2006GB002788>, 2007.
- 1690 Santer, B. D., Taylor, K. E., Wigley, T. M. L., Johns, T. C., Jones, P. D., Karoly, D. J., Mitchell, J. F. B., Oort, A. H., Penner, J. E., Ramaswamy, V., Schwarzkopf, M. D., Stouffer, R. J., and Tett, S.: A search for human influences on the thermal structure of the atmosphere, *Nature*, 382, 39–46, <https://doi.org/10.1038/382039a0>, 1996.
- Santer, B. D., Painter, J. F., Mears, C. A., Doutriaux, C., Caldwell, P., Arblaster, J. M., Cameron-Smith, P. J., Gillett, N. P., Gleckler, P. J., Lanzante, J., Perlwitz, J., Solomon, S., Stott, P. A., Taylor, K. E., Terray, L., Thorne, P. W., Wehner, M. F., 1695 Wentz, F. J., Wigley, T. M. L., Wilcox, L. J., and Zou, C.-Z.: Identifying human influences on atmospheric temperature, *Proceedings of the National Academy of Sciences*, 110, 26–33, <https://doi.org/10.1073/pnas.1210514109>, 2013.
- Santer, B. D., Po-Chedley, S., Zhao, L., Zou, C.-Z., Fu, Q., Solomon, S., Thompson, D. W. J., Mears, C., and Taylor, K. E.: Exceptional stratospheric contribution to human fingerprints on atmospheric temperature, *Proceedings of the National Academy of Sciences*, 120, e2300758120, <https://doi.org/10.1073/pnas.2300758120>, 2023.
- 1700 Schoof, C.: Ice sheet grounding line dynamics: Steady states, stability, and hysteresis, *Journal of Geophysical Research: Earth Surface*, 112, <https://doi.org/10.1029/2006JF000664>, 2007.
- Schurer, A. P., Tett, S. F. B., and Hegerl, G. C.: Small influence of solar variability on climate over the past millennium, *Nature Geoscience*, 7, 104–108, <https://doi.org/10.1038/ngeo2040>, 2014.
- Schwabe, H. and Schwabe, H.: Sonnen — Beobachtungen im Jahre 1843, *Astronomische Nachrichten*, 21, 234–235, <https://doi.org/10.1002/asna.18440211505>, 1844.
- 1705 Scripps Institution of Oceanography: The Keeling Curve, <https://keelingcurve.ucsd.edu/>, last access: 16 September 2026, 2026.
- Seidel, S. and Keyes, D. L.: Can we delay a greenhouse warming? The effectiveness and feasibility of options to slow a build-up of carbon dioxide in the atmosphere, Tech. rep., Environmental Protection Agency, Washington, DC (USA). Office of Policy Analysis, <https://www.osti.gov/biblio/5611240>, 1983.



- Setzer, J. and Higham, C.: Global trends in climate change litigation: 2025 snapshot, Policy report, Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London, <https://www.lse.ac.uk/granthaminstitute/publication/global-trends-in-climate-change-litigation-2025-snapshot/>, 2025.
- Sharma, S., Richardson, D. C., Woolway, R. I., Imrit, M. A., Bouffard, D., Blagrove, K., Daly, J., Filazzola, A., Granin, N., Korhonen, J., Magnuson, J., Marszelewski, W., Matsuzaki, S.-I. S., Perry, W., Robertson, D. M., Rudstam, L. G., Weyhenmeyer, G. A., and Yao, H.: Loss of Ice Cover, Shifting Phenology, and More Extreme Events in Northern Hemisphere Lakes, *Journal of Geophysical Research: Biogeosciences*, 126, e2021JG006348, <https://doi.org/10.1029/2021JG006348>, 2021.
- Sharma, S., Filazzola, A., Nguyen, T., Imrit, M. A., Blagrove, K., Bouffard, D., Daly, J., Feldman, H., Feldsine, N., Hendricks-Franssen, H.-J., Granin, N., Hecock, R., L'Abée-Lund, J. H., Hopkins, E., Howk, N., Iacono, M., Knoll, L. B., Korhonen, J., Malmquist, H. J., Marszelewski, W., Matsuzaki, S.-I. S., Miyabara, Y., Miyasaka, K., Mills, A., Olson, L., Peters, T. W., Richardson, D. C., Robertson, D. M., Rudstam, L., Wain, D., Waterfield, H., Weyhenmeyer, G. A., Wiltse, B., Yao, H., Zhdanov, A., and Magnuson, J. J.: Long-term ice phenology records spanning up to 578 years for 78 lakes around the Northern Hemisphere, *Scientific Data*, 9, 318, <https://doi.org/10.1038/s41597-022-01391-6>, 2022.
- Shepherd, A., Ivins, E. R., A, G., Barletta, V. R., Bentley, M. J., Bettadpur, S., Briggs, K. H., Bromwich, D. H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M. A., Lenaerts, J. T. M., Li, J., Ligtenberg, S. R. M., Luckman, A., Luthcke, S. B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J. P., Paden, J., Payne, A. J., Pritchard, H., Rignot, E., Rott, H., Sørensen, L. S., Scambos, T. A., Scheuchl, B., Schrama, E. J. O., Smith, B., Sundal, A. V., van Angelen, J. H., van de Berg, W. J., van den Broeke, M. R., Vaughan, D. G., Velicogna, I., Wahr, J., Whitehouse, P. L., Wingham, D. J., Yi, D., Young, D., and Zwally, H. J.: A Reconciled Estimate of Ice-Sheet Mass Balance, *Science*, 338, 1183–1189, <https://doi.org/10.1126/science.1228102>, 2012.
- Sherwood, S. C., Lanzante, J. R., and Meyer, C. L.: Radiosonde Daytime Biases and Late-20th Century Warming, *Science*, 309, 1556–1559, <https://doi.org/10.1126/science.1115640>, 2005.
- Sierra, C. A., Chanca, I., Andreae, M. O., de Araújo, A. C., van Asperen, H., Borchardt, L., Botía, S., Candido, L. A., Correa, C. S. C., Dias-Junior, C. Q., Eritt, M., Fröhlich, A., Gatti, L. V., Guderle, M., Hammer, S., Heimann, M., Horna, V., Jordan, A., Knabe, S., Kneißl, R., Lavric, J. V., Levin, I., Macario, K., Menger, J., Moossen, H., Quesada, C. A., Rothe, M., Rödenbeck, C., Santos, Y., Steinhof, A., Takeshi, B., Trumbore, S., and Zaehle, S.: The flask monitoring program for high-precision atmospheric measurements of greenhouse gases, stable isotopes, and radiocarbon in the central Amazon region, *Earth System Science Data*, 17, 5871–5884, <https://doi.org/10.5194/essd-17-5871-2025>, 2025.
- Snyder, L. J.: William Whewell, in: *The Stanford Encyclopedia of Philosophy*, edited by Zalta, E. N. and Nodelman, U., Metaphysics Research Lab, Stanford University, winter 2023 edn., <https://plato.stanford.edu/archives/win2023/entries/whewell/>, 2023.
- Spencer, R. W. and Christy, J. R.: Precise Monitoring of Global Temperature Trends from Satellites, *Science*, 247, 1558–1562, <https://doi.org/10.1126/science.247.4950.1558>, 1990.
- Spilhaus, A. F.: A Bathythermograph, *Journal of Marine Research*, 1, 95–100, <https://doi.org/10.1357/002224038806440647>, 1938.
- Spratt, R. M. and Lisiecki, L. E.: A Late Pleistocene sea level stack, *Climate of the Past*, 12, 1079–1092, <https://doi.org/10.5194/cp-12-1079-2016>, 2016.



- Stauffer, B., Flückiger, J., Monnin, E., Schwander, J., Barnola, J.-M., and Chappellaz, J.: Atmospheric CO₂, CH₄ and N₂O records over the past 60 000 years based on the comparison of different polar ice cores, *Annals of Glaciology*, 35, 202–208, <https://doi.org/10.3189/172756402781816861>, 2002.
- 1750 Steele, L. P., Fraser, P. J., Rasmussen, R. A., Khalil, M. A. K., Conway, T. J., Crawford, A. J., Gammon, R. H., Masarie, K. A., and Thoning, K. W.: The global distribution of methane in the troposphere, *Journal of Atmospheric Chemistry*, 5, 125–171, <https://doi.org/10.1007/BF00048857>, 1987.
- Stott, P. A., Tett, S. F. B., Jones, G. S., Allen, M. R., Mitchell, J. F. B., and Jenkins, G. J.: External Control of 20th Century Temperature by Natural and Anthropogenic Forcings, *Science*, 290, 2133–2137, <https://doi.org/10.1126/science.290.5499.2133>, 2000.
- 1755 Stuart-Smith, R. F., Otto, F. E. L., Saad, A. I., Lisi, G., Minnerop, P., Laut, K. C., van Zwieten, K., and Wetzler, T.: Filling the evidentiary gap in climate litigation, *Nature Climate Change*, 11, 651–655, <https://doi.org/10.1038/s41558-021-01086-7>, 2021.
- 1760 Sully, S., Burkepile, D. E., Donovan, M. K., Hodgson, G., and Van Woesik, R.: A global analysis of coral bleaching over the past two decades, *Nature Communications*, 10, 1264, <https://doi.org/10.1038/s41467-019-09238-2>, 2019.
- Supran, G., Rahmstorf, S., and Oreskes, N.: Assessing ExxonMobil’s global warming projections, *Science*, 379, eabk0063, <https://doi.org/10.1126/science.abk0063>, 2023.
- Tapley, B. D., Bettadpur, S., Watkins, M., and Reigber, C.: The gravity recovery and climate experiment: Mission overview and early results, *Geophysical Research Letters*, 31, <https://doi.org/10.1029/2004GL019920>, 2004.
- 1765 Teisserenc de Bort, L.: Variations de la température de l’air libre dans la zone comprise entre 8 km et 13 km d’altitude, *Comptes rendus hebdomadaires des séances de l’Académie des Sciences*, 134, 987–989, <https://gallica.bnf.fr/ark:/12148/bpt6k30902/f987.item>, 1902.
- Tett, S. F. B., Mitchell, J. F. B., Parker, D. E., and Allen, M. R.: Human Influence on the Atmospheric Vertical Temperature Structure: Detection and Observations, *Science*, 274, 1170–1173, <https://doi.org/10.1126/science.274.5290.1170>, 1996.
- 1770 Tett, S. F. B., Stott, P. A., Allen, M. R., Ingram, W. J., and Mitchell, J. F. B.: Causes of twentieth-century temperature change near the Earth’s surface, *Nature*, 399, 569–572, <https://doi.org/10.1038/21164>, 1999.
- Thomas, R. H. and Bentley, C. R.: A Model for Holocene Retreat of the West Antarctic Ice Sheet, *Quaternary Research*, 10, 150–170, [https://doi.org/10.1016/0033-5894\(78\)90098-4](https://doi.org/10.1016/0033-5894(78)90098-4), 1978.
- 1775 Tyndall, J.: I. The Bakerian Lecture.—On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absorption, and conduction, *Philosophical Transactions of the Royal Society of London*, 151, 1–36, <https://doi.org/10.1098/rstl.1861.0001>, 1861.
- UNFCCC: Report of the conference of the parties on its first session, held at Berlin from 28 March to 7 April 1995. Addendum. Part two: Action taken by the conference of the parties at its first session, Report FCCC/CP/1995/7/Add.1, United Nations Framework Convention on Climate Change, <https://unfccc.int/documents/1168>, 1995.
- 1780 UNFCCC: Kyoto Protocol to the United Nations Framework Convention on Climate Change, <https://unfccc.int>, 1997.
- United Nations: United Nations Framework Convention on Climate Change, <https://unfccc.int/resource/docs/convkp/conveng.pdf>, 1992.



- U.S. Climate Change Science Program: Temperature trends in the lower atmosphere: Steps for understanding and reconciling
 1785 differences, Synthesis and Assessment Product SAP 1.1, U.S. Climate Change Science Program and the Subcommittee on
 Global Change Research, Washington, D.C., https://www.gfdl.noaa.gov/bibliography/related_files/tmlw0602.pdf, 2006.
- Vaughan, D. G., Comiso, J. C., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot,
 E., Solomina, O., Steffen, K., and Zhang, T.: Observations: Cryosphere, in: Climate Change 2013: The Physical Science
 Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,
 1790 edited by Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and
 Midgley, P. M., pp. 317–382, Cambridge University Press, Cambridge, <https://doi.org/10.1017/CBO9781107415324.012>,
 2013.
- Velicogna, I.: Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophysical
 Research Letters*, 36, <https://doi.org/10.1029/2009GL040222>, 2009.
- 1795 Veres, D., Bazin, L., Landais, A., Toyé Mahamadou Kele, H., Lemieux-Dudon, B., Parrenin, F., Martinerie, P., Blayo, E.,
 Blunier, T., Capron, E., Chappellaz, J., Rasmussen, S. O., Severi, M., Svensson, A., Vinther, B., and Wolff, E. W.: The
 Antarctic ice core chronology (AICC2012): an optimized multi-parameter and multi-site dating approach for the last 120
 thousand years, *Climate of the Past*, 9, 1733–1748, <https://doi.org/10.5194/cp-9-1733-2013>, 2013.
- Vinnikov, K. Y., Robock, A., Stouffer, R. J., and Manabe, S.: Vertical patterns of free and forced climate variations, *Geo-
 1800 physical Research Letters*, 23, 1801–1804, <https://doi.org/10.1029/96GL01736>, 1996.
- von Schuckmann, K., Cheng, L., Palmer, M. D., Hansen, J., Tassone, C., Aich, V., Adusumilli, S., Beltrami, H., Boyer, T.,
 Cuesta-Valero, F. J., Desbruyères, D., Domingues, C., García-García, A., Gentine, P., Gilson, J., Gorfer, M., Haimberger,
 L., Ishii, M., Johnson, G. C., Killick, R., King, B. A., Kirchengast, G., Kolodziejczyk, N., Lyman, J., Marzeion, B., Mayer,
 M., Monier, M., Monselesan, D. P., Purkey, S., Roemmich, D., Schweiger, A., Seneviratne, S. I., Shepherd, A., Slater,
 1805 D. A., Steiner, A. K., Straneo, F., Timmermans, M.-L., and Wijffels, S. E.: Heat stored in the Earth system: where does
 the energy go?, *Earth System Science Data*, 12, 2013–2041, <https://doi.org/10.5194/essd-12-2013-2020>, 2020.
- von Schuckmann, K., Minière, A., Gues, F., Cuesta-Valero, F. J., Kirchengast, G., Adusumilli, S., Straneo, F., Ablain, M.,
 Allan, R. P., Barker, P. M., Beltrami, H., Blazquez, A., Boyer, T., Cheng, L., Church, J., Desbruyeres, D., Dolman, H.,
 Domingues, C. M., García-García, A., Giglio, D., Gilson, J. E., Gorfer, M., Haimberger, L., Hakuba, M. Z., Hendricks,
 1810 S., Hosoda, S., Johnson, G. C., Killick, R., King, B., Kolodziejczyk, N., Korosov, A., Krinner, G., Kuusela, M., Landerer,
 F. W., Langer, M., Lavergne, T., Lawrence, I., Li, Y., Lyman, J., Marti, F., Marzeion, B., Mayer, M., MacDougall, A. H.,
 McDougall, T., Monselesan, D. P., Nitzbon, J., Otosaka, I., Peng, J., Purkey, S., Roemmich, D., Sato, K., Sato, K., Savita,
 A., Schweiger, A., Shepherd, A., Seneviratne, S. I., Simons, L., Slater, D. A., Slater, T., Steiner, A. K., Suga, T., Szekely,
 T., Thiery, W., Timmermans, M.-L., Vanderkelen, I., Wijffels, S. E., Wu, T., and Zemp, M.: Heat stored in the Earth
 1815 system 1960–2020: where does the energy go?, *Earth System Science Data*, 15, 1675–1709, <https://doi.org/10.5194/essd-15-1675-2023>, 2023.
- WCRP Global Sea Level Budget Group: Global sea-level budget 1993–present, *Earth System Science Data*, 10, 1551–1590,
<https://doi.org/10.5194/essd-10-1551-2018>, 2018.
- Weart, S. R.: The Discovery of Global Warming: Revised and Expanded Edition, Harvard University Press,
 1820 <https://doi.org/10.4159/9780674417557>, 2008.



- Weertman, J.: Stability of the Junction of an Ice Sheet and an Ice Shelf, *Journal of Glaciology*, 13, 3–11, <https://doi.org/10.3189/S0022143000023327>, 1974.
- Weiss, R. F.: The temporal and spatial distribution of tropospheric nitrous oxide, *Journal of Geophysical Research: Oceans*, 86, 7185–7195, <https://doi.org/10.1029/JC086iC08p07185>, 1981.
- 1825 Wickham, C., Rohde, R., Muller, R. A., Wurtele, J., and Mosher, S.: Influence of Urban Heating on the Global Temperature Land Average using Rural Sites Identified from MODIS Classifications, *Geoinformatics & Geostatistics: An Overview*, 01, <https://doi.org/10.4172/2327-4581.1000104>, 2013.
- Wieczorek, M., GTN-P, Lewkowicz, A. G., Kholodov, A. L., Romanovsky, V. E., Nicolsky, D., Streletskiy, D. A., Boike, J., Heim, B., Bartsch, A., Biskaborn, B. K., Christiansen, H. H., Elger, K., and Irrgang, A. M.: GTN-P: 41 years of Mean
 1830 Annual Ground Temperature (MAGT) across latitudinal and elevational gradients in the Northern Hemisphere, v1.0, <https://doi.org/10.1594/PANGAEA.972992>, 2025.
- Wingham, D. J., Francis, C. R., Baker, S., Bouzinac, C., Brockley, D., Cullen, R., de Chateau-Thierry, P., Laxon, S. W., Mallow, U., Mavrocordatos, C., Phalippou, L., Ratier, G., Rey, L., Rostan, F., Viau, P., and Wallis, D. W.: CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields, *Advances in Space Research*, 37, 841–871,
 1835 <https://doi.org/10.1016/j.asr.2005.07.027>, 2006.
- Woodworth, P. L.: High waters at Liverpool since 1768: the UK's longest sea level record, *Geophysical Research Letters*, 26, 1589–1592, <https://doi.org/10.1029/1999GL900323>, 1999.
- Wöppelmann, G. and Marcos, M.: Vertical land motion as a key to understanding sea level change and variability, *Reviews of Geophysics*, 54, 64–92, <https://doi.org/10.1002/2015RG000502>, 2016.
- 1840 Wöppelmann, G., Pouvreau, N., and Simon, B.: Brest sea level record: a time series construction back to the early eighteenth century, *Ocean Dynamics*, 56, 487–497, <https://doi.org/10.1007/s10236-005-0044-z>, 2006.
- Wöppelmann, G., Pouvreau, N., Coulomb, A., Simon, B., and Woodworth, P. L.: Tide gauge datum continuity at Brest since 1711: France's longest sea-level record, *Geophysical Research Letters*, 35, <https://doi.org/10.1029/2008GL035783>, 2008.
- World Glacier Monitoring Service: Annual mass-change estimates for the world's glaciers, <https://doi.org/10.5904/WGMS-AMCE-2026-02-10>, 2026.
- 1845 World Meteorological Organization: Declaration of the World Climate Conference, Tech. rep., World Meteorological Organization, Geneva, Switzerland, https://dgvn.de/fileadmin/user_upload/DOKUMENTE/WCC-3/Declaration_WCC1.pdf, 1979.
- World Meteorological Organization: WMO greenhouse gas bulletin no. 19: The state of greenhouse gases in the atmosphere based on global observations through 2022, Tech. Rep. 19, World Meteorological Organization, Geneva, Switzerland, <https://wmo.int/resources/publication-series/greenhouse-gas-bulletin/wmo-greenhouse-gas-bulletin-no-19>, 2023.
- 1850 World Meteorological Organization: WMO greenhouse gas bulletin no. 20: The state of greenhouse gases in the atmosphere based on global observations through 2023, Tech. Rep. 20, World Meteorological Organization, Geneva, Switzerland, <https://wmo.int/resources/publication-series/greenhouse-gas-bulletin/wmo-greenhouse-gas-bulletin-no-20>, 2024.
- 1855 Wu, H. C., Dissard, D., Douville, E., Blamart, D., Bordier, L., Tribollet, A., Le Cornec, F., Pons-Branchu, E., Dapoigny, A., and Lazareth, C. E.: Surface ocean pH variations since 1689 CE and recent ocean acidification in the tropical South Pacific, *Nature Communications*, 9, 2543, <https://doi.org/10.1038/s41467-018-04922-1>, 2018.



- 1860 Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S. U.,
Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S., and Cogley, J. G.: Global glacier mass changes and
their contributions to sea-level rise from 1961 to 2016, *Nature*, 568, 382–386, <https://doi.org/10.1038/s41586-019-1071-0>,
2019.
- Zhang, T. Z.: Soil Temperature Station Data from Permafrost Regions of Russia (Selection of Five Stations), 1880s - 2000,
<https://doi.org/10.7265/N5C24TC5>, 2011.
- 1865 Zillman, J. W.: International cooperation in meteorology, part 1: origin and early years, *Weather*, 73, 295–300,
<https://doi.org/10.1002/wea.3217>, 2018.
- Zou, C.-Z. and Qian, H.: Stratospheric Temperature Climate Data Record from Merged SSU and AMSU-A Observations,
Journal of Atmospheric and Oceanic Technology, 33, 1967–1984, <https://doi.org/10.1175/JTECH-D-16-0018.1>, 2016.