A Pioneering Time of Discoveries in Large-Scale Tropical Meteorology : 1960 through 1972

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Abstract. The Australian Bureau of Meteorology (bom.gov.au) states that "The Madden-Julian Oscillation (MJO) is a major fluctuation in tropical weather on weekly to monthly timescale. The MJO can be characterized as an eastward moving 'pulse' of cloud and rainfall near the equator that typically recurs every 30 to 60 days." Early descriptions of the MJO were contained in two papers by Madden and Julian (1971; 1972). This paper relates the story of developments in tropical meteorology in the 1960s that led to those two papers. The decade saw the first unambiguous identification of large-scale, theoretically predicted, tropical waves. Spectral analysis was used effectively by researchers to link observations with the theoretically expected features of these waves. At the same time, longer time series of observations, faster computers, and an algorithm designed to speed up Fourier transforms, vital for spectral analysis, all became available. These developments set the stage for the oscillation to be recognized.

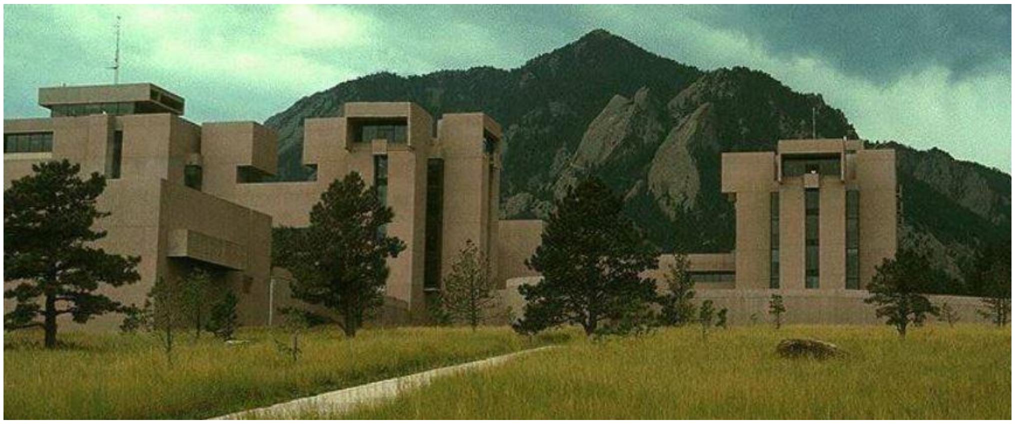
1) Introduction

Clarence Palmer, in his treatise on Tropical Meteorology, stated that whenever we get more data from the tropics "…the results usually astonish us" (Palmer, 1952). That certainly applied to the decade of the 1960s. Tropical data were becoming more accessible in digitized form suitable for treatment by computers that were also becoming available to meteorologists. Proceeding logically from Palmer's observation, the stage was set for us to be astonished and astonished we were.

The decade opened with the discovery of the Quasi-Biennial Oscillation (QBO) in the equatorial stratosphere. It is a most amazing phenomenon. The QBO is remarkable in its approximate 26-month period, its regular downward propagation, and in its large amplitude. By the mid-1960s efforts to explain the QBO led to two of the earliest unambiguous identifications of large-scale atmospheric waves predicted by theory. Simultaneously, a theory tailored just for tropical regions was published. Spectral analysis, a particularly powerful analysis tool for the tropics that sometimes requires relating events at stations 1000s of kilometers apart, was beginning to be used effectively by researchers. Also, in 1965 a fast Fourier transform algorithm suitable for coding was published that made spectral calculations orders of magnitude faster than traditional ones.

Toward the end of the decade in early 1967 a large-scale field program in the Equatorial Central Pacific was organized and carried out by the National Center for Atmospheric Research (Zipser, 1970). Work on data from this field program, the Line Islands Experiment (LIE), introduced me, a rookie researcher at NCAR, to the developments described above. In the fall of 1967,

Figure 1. *National Center for Atmospheric Research, Boulder , Colorado USA (copyright UCAR).*



during my first days at NCAR, I sat in the temporarily vacant office of an NCAR scientist who was spending a sabbatical year at the University of Chicago from where, coincidently, I had just left fresh with a Masters Degree. That scientist was Paul Julian. We were both now members of NCAR's Synoptic Meteorology Group and later the Empirical Studies Group (Fig. 2).

Figure 2. *Empirical Studies Group: left to right, Paul Julian, Roland Madden, Dennis Shea, Chester Newton (Group Head), and Harry van Loon about 1980 (copyright UCAR).*

Julian was a former student of Hans Panofsky who pioneered the use of spectral analysis in meteorology (Panofsky, 1955). As a result, Julian was well versed in the technique. He published a review of it and showed how spectral analysis could be applied to geophysical data (Julian, 1967). He had also done a spectral analysis of 21 years of zonal index data (a measure of the strength of the westerlies) to test quantitatively the notion of an index cycle of three to eight weeks (Julian, 1966) that had been qualitatively accepted as real (e.g. Petterssen, 1956). Results suggested that the zonal index could be adequately modeled by a first order autoregressive process with little evidence of a preferred three to eight week variation.

Upon Julian's return to NCAR in 1968 he guided me in my efforts to apply spectral analysis to the LIE winds. By late 1970, our collaboration had expanded and eventually led to a description of what is now referred to as the MJO, or Madden and Julian Oscillation after two papers in the early 1970s (Madden and Julian:1971; 1972; hereafter MJ71 and MJ72). What follows is the story, as I remember, of our collaboration that led to those two papers and of the background outlined above that influenced us.

2) Background

2-1) Discovery of the Quasi-Biennial Oscillation

Graystone presented a time-height diagram of zonal, or u-wind, in the stratosphere over Christmas Island, 2N and 158W (Graystone, 1959). He had only two years of data and could not recognize the amazing QBO which he was sampling. He only remarked that there was an absence of annual cycle and a presence of large vertical shears. Ebdon (1961) and Reed et.al. (1961) extended the record beyond two years, and they were able to identify east and west wind regimes propagating downward in the stratosphere that varied by as much as 40 m/s. The average time scale of the wind shifts was 26 months. I am sure that Palmer, who left us in 1973, was astonished along with most meteorologists by the amazing behavior of the QBO. The QBO increased interest in tropical meteorology. Although the QBO did not affect our later work directly, some subsequent research aimed at explaining its behavior did.

2-2) Theory of Waves in the Equatorial Atmosphere

Matsuno (1966) published a theoretical paper specifically tailored to the equatorial region. He showed how his approximate equations are an asymptotic case of the Laplace Tidal Equations

(LTE) that address the behavior of a thin fluid on the full, rotating, spherical earth. The wave solutions of the LTEs fall into two classes (Hough, 1898): The waves of the First Class are eastward and westward traveling gravity waves; waves of the Second Class are westward propagating, and called Rossby or normal mode Rossby-Haurwitz waves (Rossby et.al., 1939; Haurwitz, 1940a ; 1940b). Similarly, Matsuno's equations yield two classes of waves, inertia gravity waves and Rossby waves, which are equivalent to approximate forms of waves of the First and Second Class.

Two waves, or modes, described by Matsuno are of special interest. One mode behaves like a gravity wave, or wave of the First Class, for waves long relative to the fluid depth and like a Rossby wave, or wave of the Second Class, for shorter waves (see Longuet Higgins, 1968: Fig. 5 for zonal wavenumber 4). This mixed Rossby gravity wave (MRGW) is reflected in variations of the meridional, or v-wind.

The second important mode is a special type of wave of the First Class, the atmospheric Kelvin wave. Unlike the MRGW, the equatorial Kelvin wave is confined to variations in the u-wind. It gets its name from work by Lord Kelvin (Thomson, 1879) who studied waves that propagate parallel to sides of a canal. The interesting aspect of atmospheric, equatorial Kelvin waves is the fact that the change in sign of the Coriolis force at the equator acts dynamically as the canal side (or a coast line).

In his 1966 paper, Matsuno posed the question of whether the waves he described exist in actual atmospheric conditions. The answer came back quickly in research aimed at explaining the QBO.

2-3) Discovery of MRGWs and Kelvin Waves in Observations

Yanai and Maruyama (1966), searching for evidence of eddy disturbances that might converge enough momentum to drive the QBO, discovered alternating downward propagating north and south winds in the stratosphere over the central tropical Pacific during northern spring and early summer of 1958. The average period of the oscillating v-winds was around five days. These varying winds were shown to behave similarly to those of MRGW (Maruyama, 1967).

The discovery of Kelvin waves soon followed (Wallace and Kousky, 1968). Like Yanai and Maruyama (1966), Wallace and

Kousky were initially motivated by problems related to the momentum budget of the QBO. They found fluctuations in the u-wind in the stratosphere at stations in the Pacific and Caribbean with an average period of 15 days. Wallace and Kousky showed that the structure and behavior of the oscillations were consistent with those of the theoretically predicted equatorial Kelvin wave.
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It should be said that the discovery of MRGW and Kelvin waves were among the first unambiguous identifications of large-scale atmospheric waves predicted by theory. With the exception of the findings of Kubuto and Iida (1954) that showed the presence of normal mode Rossby-Haurwitz waves, in the mid-60s there was little observational evidence of theoretically predicted large-scale waves. The important papers of Eliason and Machenhauer (1965; 1969) identifying normal mode Rossby-Haurwitz waves were either just being disseminated or still on the drawing boards, as was Ray Deland's work (e.g. Deland, 1965).

2-4) Use of Spectral Analysis in Studying Tropical Data

Besides showing the similarity between Yanai-Maruyama waves and Matsuno's MRGWs, Maruyama (1967) used spectral analysis in the diagnosis of the data. It showed spectral peaks, or extra variance, in the 4-5 day period range quantifying the subjectively estimated period in Yanai and Maruyama (1966).

Wallace and Kousky (1968) used spectral analysis to identify aspects of the theoretical Kelvin wave in the upper air data that they were examining. For example, cross-spectra between zonal wind and temperature quantified a quadrature relationship predicted by theory and underscored the power of spectral analysis when diagnosing wave-like behavior.

Yanai and colleagues at the University of Tokyo and Wallace and colleagues at the University of Washington then expanded their use of spectral analysis to further diagnose tropical wave motions. Yanai et.al. (1968) computed spectra and cross-spectra of the v-wind between 17 Pacific stations at 34 levels from the surface to the lower stratosphere. Data were from the period April to July of 1962. The analyses allowed them to estimate vertical and horizontal structures of 4-5 day period disturbances. Among other things, they found that in the lower troposphere, the v-wind spectra had spectral peak near 4-days and phase angles that suggested an eastward slope with height.

Wallace and Chang (1969) studied data from the July to December 1963 period. They concentrated on the troposphere below 500hPa. They saw little evidence of vertical propagation in the 4-5 day v-wind variations in contrast to that in the1962 data examined by Yanai et.al. (1968). Wallace and Chang looked at three additional six month periods during the two years 1963 through 1964 at Truk Island (7N, 152E, now Chuuk). They determined that besides the vertical structure changing with time, the 4-5 day spectral peak in the v-wind itself varied with time as well.

Wallace and Chang also detected the 5-day normal mode Rossby-Haurwitz wave that had recently been identified by Eliasen and Machenhaur (1965; 1969) and Deland (1965). Most important for the MJO story is that they reported on a low frequency oscillation "…which could not be adequately resolved with the limited period of record" (Wallace and Chang, 1969). Like Graystone's limited look at the QBO, Wallace and Chang's low frequency oscillation may have been the MJO awaiting a longer record to be recognized.

Spectral analyses by Yanai, Wallace, and colleagues had a major influence on our later studies. Much of the work described above was summarized by Wallace (1969) along with examples of the use of spectral analysis. Innovative uses of spectral analyses of these tropical data were further summarized by Wallace (1971) and by Julian (1971).

2-5) The Fast Fourier Transform

Spectral analysis and cross-spectral analysis involve Fourier transforming the time series data directly (direct method), or Fourier transforming the auto-covariance function determined from the time series data (indirect method). In either case the traditional Fourier transform requires considerable multiplications. In 1965, Cooley and Tukey (1965) published an algorithm suitable for computer calculations of a fast Fourier transform (FFT). The FFT sped up computations enormously. For a time series N values long the traditional transform required N*N multiplications. Depending on how factorable N is, the FFT required about $N*\mathrm{Log}_2(N)$ or a speed up factor of $N/\mathrm{Log}_2(N)$ (Cooley and Tukey, 1965; Cooley, 1987). For N=1000 the speed up factor is 100. So the door was opened for much faster transforms.

It is interesting to note that Cooley reports that his first interaction with Tukey was at Princeton's Institute for Advanced

Study Program in 1953 where Tukey was a consultant and he, Cooley, was a programmer in Von Neuman's Numerical Weather Prediction Group. Cooley programmed a spectral analysis routine for Tukey (Cooley, 1987). Ten years later the two would team up to forever alter the way we compute a Fourier transform.

3) Work Leading to the Identification of the MJO

3-1) The Line Islands Experiment Upper Air Data and the Honolulu Tropical Meteorology Conference of 1970

The above happenings laid the groundwork for Julian and my work that led to a description of the MJO. The role that spectral analysis played in the discoveries of MRGWs and Kelvin waves, and its demonstrated value describing tropical, tropospheric disturbances suggested that we should apply it to the LIE data.

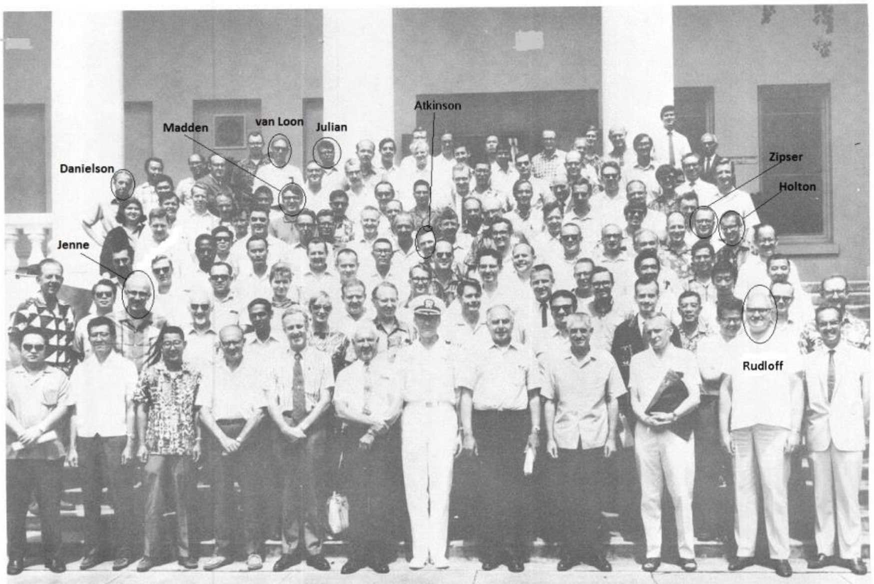
Backing up a little, in early 1967 I was anticipating completing the requirements for a Masters Degree at the University of Chicago. I had spent the prior two years studying under Professor Tetsuya Fujita and had learned a lot about Satellite Meteorology. Given a satellite's attitude in space and its subpoint, I had learned to "grid" or add latitude/longitude lines to any picture. This skill put me in a good position to qualify for a job opening at the newly started NCAR. NCAR was in the process of carrying out the LIE under the direction of Chief Scientist Ed Zipser. The LIE was motivated in part to provide ground truth for ATS-1, the first equatorial geosynchronous meteorological satellite. It was launched in December 1966 (Zipser, 1970). When I arrived in Boulder in September of 1967, my first assignment was to grid pictures taken by ATS-1 earlier that year during the LIE.

As the picture gridding neared completion, probably in late October 1967 a large shipping crate appeared in the hall outside my office. I learned that it was full of punch cards containing thermodynamic, azimuth, and elevation information of more than 800 rawinsondes recorded during the LIE. It was then my responsibility to turn these raw data into wind speed and direction, temperatures, and moisture variables. Fortunately, NCAR scientist Ed Danielson and summer student Bob Gall, who years later would become a Division Director at NCAR, had written a computer program to do just that for the LIE data. I teamed with Dennis Joseph, a data expert and member of NCAR's Computing Facility's Data Support Section, to finish the job. The thermodynamic and wind data were published in February 1971 (Madden et.al., 1971).

In the meantime, we had the opportunity to look at the data. I am not certain, but I think it is likely that when I arrived at NCAR in 1967, I was unaware of the important discoveries summarized above. Probably in early 1968, one of my new NCAR colleagues drew my attention to the Yanai and Maruyama (1966) paper because of its relevance to LIE stratospheric data. Certainly by early 1969, I had learned of the innovative ways that Yanai, Wallace and colleagues were using spectral analysis in their work. It was natural to do similar analyses for the LIE period.

By mid-1968, I had been moved to a more permanent office and Julian had returned from Chicago. In the months to follow, with his help, I computed spectra of LIE upper air meridional winds and was preparing a paper to be delivered at the Honolulu Tropical Meteorology Meeting planned for June of 1970. Figure 3 is a photograph of meeting participants (American Meteorological Society/World Meteorological Organization, 1970). Many who are mentioned in the text are circled. My paper was entitled "Wave Disturbances over the Equatorial Pacific during the Line Islands Experiment" (Madden, 1970). Results did not show the 4-5 day spectral peaks in the lower troposphere that were present during April-July of 1962 reported by Yanai et.al. (1968) further confirming the variability of the tropospheric spectra.

Figure 3. *Participants in the Honolulu Conference, 1970. (photo credit American Meteorological Society/World Meteorological Organization, 1970). Key to all in the photo can be seen in the AMS/WMO reference or in the Bulletin of the American Meteorological Society Supplemental Materials (Madden, 2019).*



Participants in the Honolulu Conference (from *Proc. of the Sym. on Tropical Meteorology*, Honolulu, HI, 1970).

In the discussion that followed my talk, Gary Atkinson from the U. S. Air Force made the observation that the nascent spectral studies of the tropics had been based on relatively short time series (the LIE time series were only 47 days long). He suggested that there now were long time series available from Pacific stations and it would be good to compute spectra based on them to better assess the "…variability and/or stability…" of results. We knew that Atkinson was right and that Julian and I were in the perfect position to look at longer time series. The NCAR Data Support Section headed by Roy Jenne had begun to collect some of these long series. Julian had a FFT code based on Cooley and Tukey's algorithm, and we had access to a Control Data Corporation 6600. The CDC 6600 had a clock speed of 10MHz and a memory of 65kb, 60-bit words (NCAR,2022) which, though orders of magnitude slower and smaller than a modern cell phone, made it the most powerful computer available for meteorological research at the time. Upon our return from Honolulu I turned my attention to investigating the longest time series available from the equatorial region.

Figure 4. *CDC 6600 (copyright UCAR).*

3-2) Studying Longer Time Series

3-2-1) MJ71

Our motivation was to examine time variation in the spectra of tropical observations in the 4-5 day period range. The longest record available for this purpose was rawinsonde data from 3584 days measured at Canton Island (3S, 172W, now Kanton). With the long record we could resolve lower frequency variations that had not yet been investigated. Almost immediately our attention shifted from documenting time variations in 4-5 day disturbances to investigating variations in the 40-50 day range because of results typified by Fig. 5. Coherence squared shown in Fig. 5 is similar to correlation as a function of frequency. It shows a broad maximum with largest values in the 40-50 day range. Corresponding phase angles (not shown) indicated that surface pressures and 850 hPa u-winds were in phase and 850 and 150 hPa u-winds were out-of - phase.

We had no a priori reason to expect this result so usual statistical tests were not appropriate. Julian discussed prior versus posterior statistical tests in the paper we prepared (MJ71), and demonstrated that it would be rare to have such high coherence values if the time series were not related. He expanded on this argument in his paper published in 1971 (Julian, 1971).

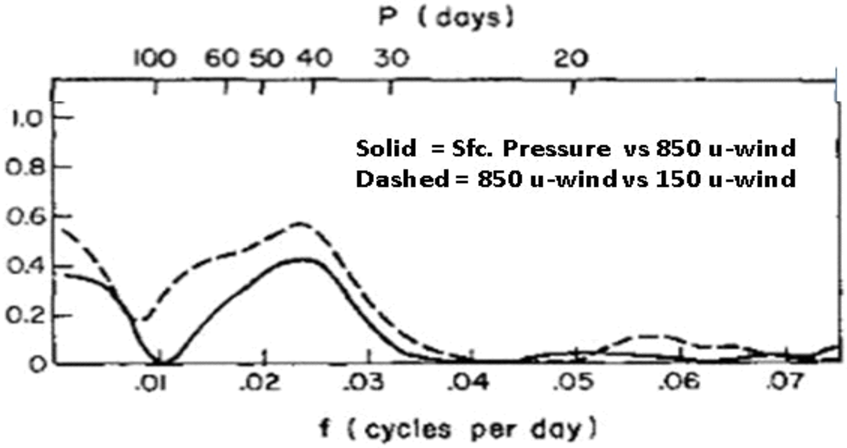


Figure 5. *Coherence squared between 850 and 150 u-winds (dashed) and between surface pressure and the 850 u-winds (solid) based on Kanton pressure and upper air data . The 0.1% prior confidence level assuming a null of no Coherence is 0.25. (adapted from MJ71)*

Considering phase angles between participating variables we concluded the evidence pointed to a large circulation cell orientated in the equatorial plane with a node where the u-wind switches direction in the 600-500 hPa region. Neither the spectra nor cross-spectra involving the v-wind showed maxima in the 40-50 day range so we concluded that it was not involved. We will see that data from more stations confirmed that the oscillation was indeed the manifestation of large circulation cells, but, because none of our spectra differentiated between seasons, our conclusion about v-wind was wrong.

The paper describing the results from Kanton was submitted to the Journal of the Atmospheric Sciences on 21 December 1970. A letter dated 12 March 1971 from editor S. I. Rasool stated that reviews, plural, were in but relatively minor comments from only one review were attached. We addressed the reviewer's comments and the paper was published in July 1971 (MJ71).

3-2-2) MJ72

Working to get a full picture of the phenomenon that we were seeing at Kanton, we assembled station pressure data from 25 tropical stations (16 were within 15^0 of the equator) and upper air data from six stations all located within 15^0 of the equator and spaced around its full circumference. Cross-spectra of the pressure data revealed that the 40-50 day disturbance propagated eastward and spread poleward but was strongest within 10^0 of the equator. Based on cross-spectra of upper air data from the six stations, we made a figure that summarized the status at all stations and levels that were coherent with Kanton pressure when Kanton pressure was a relative maximum (Fig. 6 of MJ72). That helped us to envision the zonally orientated circulation cells and their eastward movement.

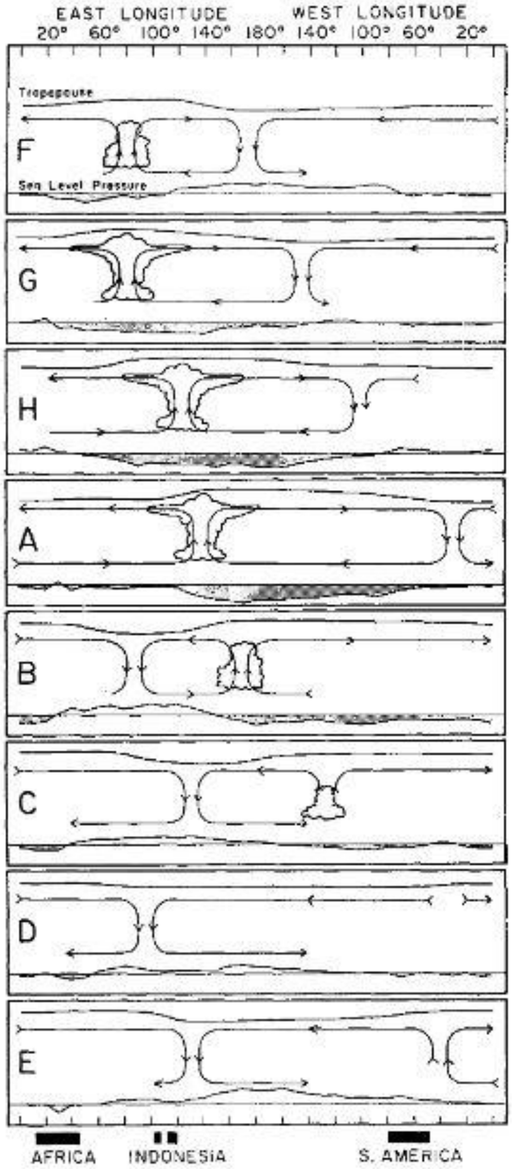
To supplement the spectral evidence with a synoptic picture of the disturbance based directly on time-series data, we turned to data from the International Geophysical Year, 1957-1958. (IGY). Willy Rudloff had presented a paper at the Honolulu meeting titled "Measurable Seasonal Variations in the Total Mass of the Atmosphere" (Rudloff, 1970) which was based on gridpoint pressure data digitized from IGY World Weather Maps prepared by his office, the Seewetteramt in Hamburg. I wrote to him on 12 March 1971 about our interest in the tropical zone and he kindly sent us the grid point sea level pressure data on computer cards which was a standard way of storing and transferring data. We also tabulated and prepared punched cards containing IGY upper air data from printouts available in the NCAR library. In 1970, all of our programs and much of our data were contained on punch cards. Typical of the time, Fig.6 shows two NCAR programmers submitting their card decks to be read into the CDC 6600.

Figure 6. *Two programmers (left) submitting their card decks to the operator for reading into the CDC 6600 about 1970 (copyright UCAR).*

We computed a composite wave by first selecting dates during the IGY period when 45-day band-pass filtered Kanton pressure was at a relative minimum, and separately at a maximum and at six more intermediate times. The IGY data were then averaged for each of the set of eight dates separately. A pictured emerged that was consistent with the spectral results. The sea level pressure perturbations moved eastward as did those of the zonal wind. There was a wave on the tropopause and some evidence of water vapor mixing ratio variations consistent with eastward moving deep convection. A more detailed discussion of the first time we saw eastward propagation in the IGY pressures is contained in Hand (2015).

This spectral and synoptic evidence led to a description of the 40-50 day oscillation that is contained in Fig. 7. Phase E corresponds to the time when station pressure is a relative maximum at Kanton and Phase A when it is a minimum. We had no precipitation or cloud data at the time but included an indication of varying convection because of the low level convergence in the u-wind, mixing ratio changes, and the changing height of the tropopause.

Figure 7. *Schematic depiction of the time and space variations of the oscillation. Phase "A" ("E") is the time of lowest ("highest") pressure at Kanton. Other phases are intermediate times and for a 48-day period are approximately six days apart. Anomaly pressures are indicated at the bottom of each panel with negative anomalies shaded. Circulation cells are based on u-wind variations. Regions of enhanced convection are proposed based on u-wind convergence/divergence, tropopause height differences (top line), and mixing ratio changes.*



We submitted our paper describing the above results on 6 April 1972. Editor Rasool, in a letter dated 8 May 1972, stated that "… your paper has been found acceptable for publication …" This time comments from two reviewers were included. Reviewer 1 accepted the paper on the condition that results from Gan Island (0.7S, 73.2E) are included. The reviewer stated that "… Gan Island is strongly affected by the Asian Monsoon which seems to possess a 30-40 day period", a qualitative assessment which was quantitatively documented by Yasunari (1979; 1980).

Fortunately, during the review process we had begun to examine spectra and cross-spectra for Gan data, and results were easily added to Figs. 1 and 4 of MJ72. Reviewer 2 gave us eight constructive comments which required only small changes. The paper was published in September 1972. We pointed out that the oscillation was a broad-band one, but called it the "40-50 Day Oscillation" because spectral maxima of the various variables most often fell in that range. The "MJO" reference began being used more frequently after it appeared in the title of two papers (Swinbank et. al., 1988; Lau et. al., 1988).

Table 1 shows the sequence of submission and publication dates for some of the relevant papers. Recently, Li et.al. (2018) have brought to the attention of the international meteorology community a paper relating low latitude basic flow and the occurrence of typhoons written in Chinese and published already in 1963 that shows MJOs in the zonal wind during the 1958 – 1960 period. In the paper, which is not listed in Table 1 but is now a part of the history, Xei et.al. (1963) observed that the u-wind exhibited an oscillatory period of about one and a half month.

Table *1* *Chronology of Some Relevant Papers Ordered by Submission Date*

Paper	**Date Submitted**	**Date Published**
Cooley and Tukey (1965)	17 August 1964	April 1965
Matsuno (1966)	15 November 1965	February 1966
Julian (1966)	6 December 1965	May 1966
Yanai and Maruyama (1966)	19 July 1966	October 1966
Longuet-Higgins (1968)	28 November 1966	February 1968
Julian (1967)	1 February 1967	September 1967
Maruyama (1967)	28 April 1967	October 1967
Wallace and Kousky (1968)	1 February 1968	September 1968
Yanai et. al. (1968)	26 February 1968	August 1968
Wallace and Chang (1969)	24 February 1969	September 1969
Wallace (1969)		October 1969
Wallace (1971)	December 1970	August 1971

Madden and Julian (1971)	21December 1970	July 1971
Julian (1971)	23 February 1971	December 1971
Madden and Julian (1972)	6 April 1972	September1972

4) Epilogue

4-1) Developments Related to Two of Our Conclusions

The clouds in Figure 7 were based on circumstantial evidence. During the decade after MJ72, published papers using wavenumber-frequency analysis of satellite brightness data (Gruber, 1974; Zangvil, 1975); case studies and spectral analysis (Yasunari, 1979; 1980); and compositing (Julian and Madden, 1981), provided evidence of cloud behavior consistent with Fig. 7

Secondly, we concluded in MJ71 that the spectral results suggested that the v-wind was not involved in the oscillation. Specifically, coherence squares between the v-wind and u-wind were not significantly different from zero. Fifteen years later, we learned that u and v are coherent and out-of-phase in Northern Winter and coherent and in-phase in Northern Summer. This in- and out-of-phase switch between seasons resulted in small cospectra and a resulting small coherence when, in MJ71, we averaged over the entire year. The seasonal phase variations are consistent with surges in the wind from summer to winter hemispheres (see arguments in Madden, 1986).

4-2) Reception of MJ71 and MJ72

From 1972 through 1979, MJ71 and MJ72 were cited 17 and 19 times respectively according to the Web of Science. It is interesting to note that five of the MJ71 citations did not mention the oscillation itself, but rather they referenced the spectral analysis method or Julian's discussion about posterior statistical tests. Jim Holton at the University of Washington found the oscillation interesting and in a letter to me shortly after MJ71 appeared offered prescient ideas about its spatial structure based on some of his modeling work (see Wallace, 2014); ideas which, unfortunately, we did not follow up on.

Interest in the two papers picked up in the 1980s when MJ71 and MJ72 were cited 136 and 140 times respectively. A circumstance that led to increased interest was the summer MONEX experiment during May through July of 1979. The MJO was active during that period.（e.g. Krishnamurti and Subrahmanyam,1982).

5) Conclusions

The path to the initial description of the MJO starts with the discovery of the QBO in 1961. The QBO stimulated studies aimed at explaining its remarkable behavior. These studies applied spectral analysis in innovative ways to describe tropical waves. The availability of relevant data was increasing along with the computer power needed for efficient analyses. The fast Fourier transform which sped up spectral calculations was first coded for computers in mid-1960. The descriptions contained in MJ71 and MJ72 relied on the power of spectral analysis.

Considerable advances in understanding of the MJO have been made in the 50 intervening years since MJ72. For up to date information look at:

WGNE MJO Task Force – a Working Group of the WMO, https://wgne.net/activities/on-going-activities/wgne-mjo-task-force/

MJO work at the United States Climate Prediction Center, https://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/mjo.shtml

MJO monitoring and research at Australian BOM, http://www.bom.gov.au/climate/mjo/

S2S Prediction Project, http://s2sprediction.net

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References:

American Meteorological Society/World Meteorological Organization： Proc. Symp. on Tropical Meteorology, June 2-11. U. of Hawaii, Honolulu, 1970

Cooley, J. W. : The re-discovery of the fast Fourier transform algorithm. Microchim. Acta (Wien), **3**, 33-45, 1987.

Cooley, J. W., and J. W. Tukey : An algorithm for the machine calculations of complex Fourier series., Math. Comp., **19**, 297, 1965.

Deland, R. J. : Some observations of the behavior of spherical harmonic waves. Mon. Wea. Rev., **93**, 307-312, 1965.

Ebdon, R. A. : Some notes on the stratospheric winds at Canton Island and Christmas Island. J. Royal Meteor. Soc., **87**, 322-331,1961.

Eliasen, E. and B. Machenhauer : A study of the fluctuations of atmospheric planetary flow patterns represented by spherical harmonics. Tellus, **17**, 220-238, 1965.

Eliasen, E. and B. Machenhauer : On the observed large-scale atmospheric wave motions. Tellus, **21**, 149-165, 1969.

Graystone, P. : Meteorological Office Discussion – Tropical Meteorology. Met. Mag., **88**, 113-119, 1959.

Gruber, A. : Wavenumber-frequency spectra of satellite measured brightness in Tropics, J. Atmos. Sci., **31,** 1675-1680, 1974.

Hand, E. : The Storm King, Science, **350,** 22-25, 2015.

Haurwitz, B. : The motion of atmospheric disturbances. J. Mar. Res., **3,** 35-50, 1940a.

Haurwitz, B. : The motion of atmospheric disturbances on the spherical earth. J. Mar. Res., **3,** 254-267, 1940b.
1940b

Hough, S. S. : On the application of harmonic analysis to the dynamical theory of tides II. On the general integration of LaPlace's tidal equations. Phil. Trans., A, **191**, 139-185, 1898.

Julian, P. R. : The Index Cycle: a cross-spectral analysis of zonal index data. Mon. Wea. Rev., **94**, 283-293, 1966.

Julian, P. R. : Variance spectrum analysis. Water Resources Research, **3**, 831-845, 1967.

Julian, P. R. : Some aspects of the variance spectra of synoptic scale tropospheric wind components in mid-latitudes and in the tropics. Mon. Wea. Rev., **99,** 954-965, 1971.

Julian, P.R., and R. A. Madden : Comments on a paper by T. Yasunari, a quasi-stationary appearance of 30 to 40-day period in cloudiness fluctuations during the summer monsoon over India. J. Met. Soc. Japan, **59,** 435- 437, 1981.

Krishnamurti, T. N., D. Subrahmanyam : The 30-50 day mode at 850 mb during MONEX. J. Atmos. Sci., **39,** 2088-2095, 1982.

Kubota, S. and Iida, M. : Statistical characteristics of atmospheric disturbances. Pap. Meteorol. Geophys. **5**, 22-34, 1954.

Lau, N. C., I. M. Held, and J. D. Neelin : The Madden-Julian Oscillation in an idealized general circulation model. J. Atmos. Sci, **45**, 3810-3832, 1988.

Li, T., L. Wang, M. Peng, B. Wang, C, Zhang, W. Lau, and H-C Kuo : A paper on the tropical intraseasonal oscillation published in 1963 in a Chinese journal. Bul. Amer. Meteor. Soc., **100,** 1765-1779, 2018.

Longuet-Higgins, M. S. : The Eigen functions of LaPlace's tidal equations over a sphere. Phil. Trans. Roy. Soc. London, Ser. A, **262**, 511-607, 1968.

Madden, R., A. : AMS/WMO, Wave disturbances over the equatorial Pacific during the Line Islands Experiment. Proc. Symp. on Tropical Meteorology, June 2-11. U. of Hawaii, Honolulu, 1970.

Madden, R. A. : Seasonal variations of the 40-50 day oscillation in the tropics. J. Atmos. Sci., **43**, 3138-3158, 1986.

Madden, R. A., E. J. Zipser, E. F. Danielson, D. H. Joseph, and R. Gall, : Rawinsonde data obtained during the Line Island Experiment. Vol.1 Data reduction procedures and thermodynamic data. 340pp; Vol II, Wind data. 308pp. NCAR Technical Note TN/STR – 55, 1971.

Madden, R. A., and P. R. Julian : Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific. J. Atmos. Sci. **28**, 702-708, 1971.

Madden, R. A., and P. R. Julian : Description of global-scale circulation cells in the tropics with a 40-50 day period. J. Atmos. Sci., **29**, 1109-1123, 1972.

Maruyama, T. : Large-scale disturbances in the equatorial lower stratosphere. J. Meteor. Soc. Japan, **45**, 391-408, 1967.

Matsuno, T. : Quasi-geostrophic motions in the equatorial area. J. Meteor. Soc. Japan, **44**, 25-43, 1966.

NCAR, 2022: Supercomputing history. https://www2.cisl.ucar.edu/ncar-supercomputing-history.

Palmer, C. E. : Tropical Meteorology. J. Royal Meteor. Soc., **78,** 126-164, 1952.

Panofsky, H.A. : Meteorological applications of power-spectrum analysis. Bull. Amer. Meteor. Soc., **36**, 163-166, 1955.

Petterssen, S. : Weather Analysis and Forecasting, McGraw-Hill Book Co., Inc., New York, 428 pp, 1956.

Reed, R. J., W. J. Campbell, L. A. Rasmussen, and D. G. Rogers : Evidence of a downward-propagating annual wind reversal in the equatorial stratosphere. J. Geophys. Res., **66**, 813-818, 1961.

Rossby, C-G. et al. : Relations between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semipermanent centers of action. J. Mar. Res., **2,** 38-55, 1939.

Rudloff, W. : AMS/WMO, Measurable seasonal variations in the total mass of the atmosphere. Proc. Sym. on Tropical Meteorology, June 2-11, U. of Hawaii, Honolulu, 1970

Swinbank, R., T. N. Palmer, and M. K. Davey : Numerical simulation of the Madden and Julian Oscillation. J. Atmos. Sci., **45**, 774-778, 1988.

Thomson, W. : On gravitational oscillations of rotating water. Proc. Roy. Soc., Edinburg, **10**, 92-100, 1879.

Wallace, J. M. : Some recent developments in the study of tropical wave disturbances. Bul. Amer. Met. Soc., **50**, 792-799, 1969.

Wallace, J.M. : Spectral studies of tropospheric wave disturbances in the tropical western Pacific. Rev. Geophys. Space Phys., **9**, 557–612, 1971.

Wallace, J. M., and V. E. Kousky : Observational evidence of Kelvin waves in the tropical stratosphere. J. Atmos. Sci., **25**, 900-907, 1968.

Wallace, J. M. and C.-P. Chang : Spectrum analysis of large-scale wave disturbances in the tropical lower troposphere. J. Atmos. Sci.., **26**, 1010-1025., 1969.

Wallace, J. M. : A biographical memoir. National Academy of Science, 27pp, 2014. www.nasonline.org/memoirs.

Xie, Y.-B., S.J Chen, I.-L. Zhang, and Y,-L. Hung : A preliminary statistic and synoptic study about the basic currents over southeastern Asia and the initiation of Typhoons (in Chinese), Acta Meteor. Sin ., 33, 206-217, 1963.

Yanai, M., and Maruyama, T. : Stratospheric wave disturbances propagating over the equatorial Pacific. J. Met. Soc. Japan, **44**, 291-294, 1966.

Yanai, M., T. Maruyama, T. Nitta, and Y. Hayashi, 1968: Power spectra of large-scale disturbances over the tropical Pacific., J. Met. Soc. Japan, **46**, 308-323.

Yasunari, T. : Cloudiness fluctuations associated with the Northern Hemisphere Summer Monsoon. J. Met. Soc. Japan, **57**, 227-242, 1979.

Yasunari, T. : A quasistationary appearance of 30 to 40 day period in the cloudiness fluctuations during the Summer Monsoon over India. J. Met. Soc. Japan, **58**, 225-229, 1980.

Zangvil, A. : Temporal and spatial behavior of large-scale disturbances in tropical cloudiness deduced from satellite brightness data. Mon. Wea. Rev., **103**, 904-920, 1975.

Zipser, E. J. : The Line Islands Experiment, its place in tropical meteorology and the rise of the fourth school of thought. Bull. Amer. Meteor. Soc., **51**, 1136-1146, 1970.

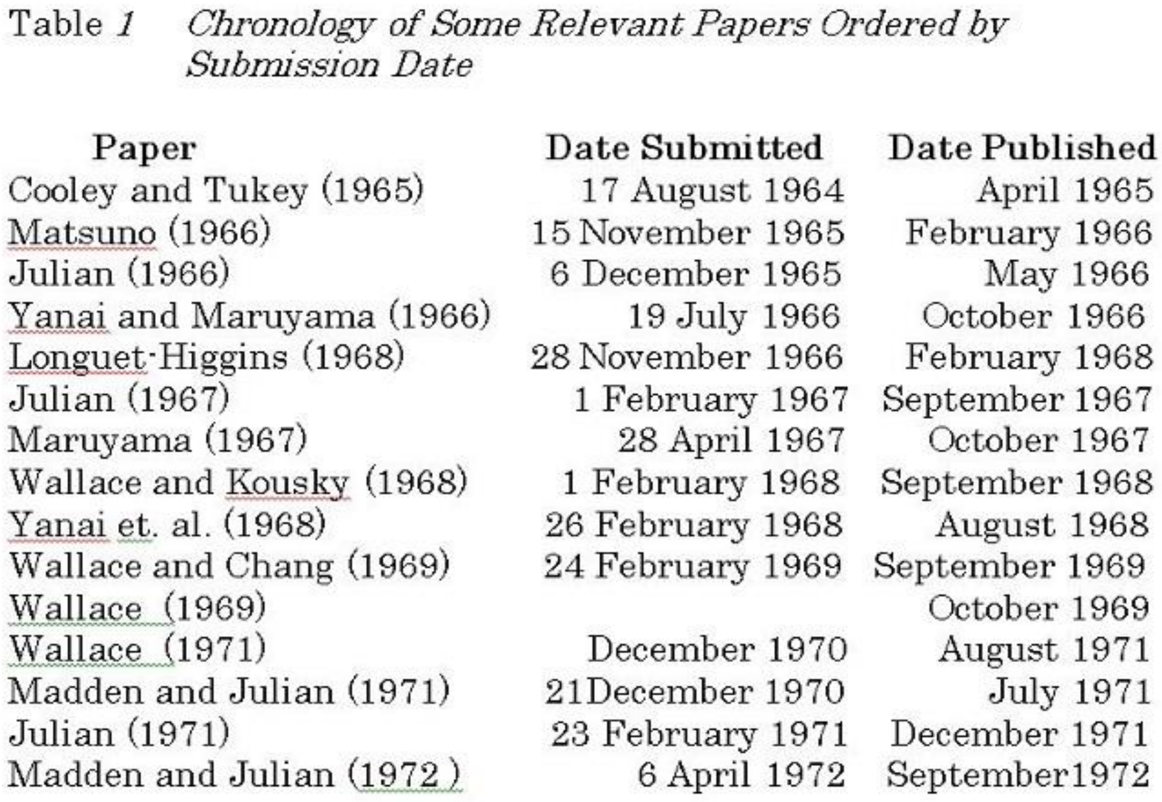

Table *1* *Chronology of Some Relevant Papers Ordered by Submission Date*

Paper	Date Submitted	Date Published
Cooley and Tukey (1965)	17 August 1964	April 1965
Matsuno (1966)	15 November 1965	February 1966
Julian (1966)	6 December 1965	May 1966
Yanai and Maruyama (1966)	19 July 1966	October 1966
Longuet-Higgins (1968)	28 November 1966	February 1968
Julian (1967)	1 February 1967	September 1967
Maruyama (1967)	28 April 1967	October 1967
Wallace and Kousky (1968)	1 February 1968	September 1968
Yanai et. al. (1968)	26 February 1968	August 1968
Wallace and Chang (1969)	24 February 1969	September 1969
Wallace (1969)		October 1969
Wallace (1971)	December 1970	August 1971
Madden and Julian (1971)	21December 1970	July 1971
Julian (1971)	23 February 1971	December 1971
Madden and Julian (1972)	6 April 1972	September1972

Figure 1. National Center for Atmospheric Research, Boulder , Colorado USA (copyright UCAR).

Figure 2. Empirical Studies Group: left to right, Paul Julian, Roland Madden, Dennis Shea, Chester Newton (Group Head), and Harry van Loon about 1980 (copyright UCAR).

Figure 3. Participants in the Honolulu Conference, 1970. (photo credit American Meteorological Society/World Meteorological Organization, 1970). Key to all in the photo can be seen in the AMS/WMO reference or in the Bulletin of the American Meteorological Society Supplemental Materials (Madden, 2019).

Figure 4. CDC 6600 (copyright UCAR).

Figure 5. Coherence squared between 850 and 150 u-winds (dashed) and between surface pressure and the 850 u-winds (solid) based on Kanton pressure and upper air data . The 0.1% prior confidence level assuming a null of no Coherence is 0.25. (adapted from MJ71)

Figure 6. Two programmers (left) submitting their card decks to the operator for reading into the CDC 6600 about 1970 (copyright UCAR).

Figure 7. Schematic depiction of the time and space variations of the oscillation. Phase "A" ("E") is the time of lowest ("highest") pressure at Kanton. Other phases are intermediate times and for a 48-day period are approximately six days apart. Anomaly pressures are indicated at the bottom of each panel with negative anomalies shaded. Circulation cells are based on u-wind variations. Regions of enhanced convection are proposed based on u-wind convergence/divergence, tropopause height differences (top line), and mixing ratio changes.