

Chapter 3

Michio Yanai and Tropical Waves

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ABSTRACT

Insights by Professor Michio Yanai on tropical waves, which have been vital ingredients for progress in tropical meteorology over the last half-century, are recollected. This study revisits various aspects of research on tropical waves over the last five decades to examine, in Yanai's words, "the nature of 'A-scale' tropical wave disturbances and the interaction of the waves and the 'B-scale' phenomena (cloud clusters)," the fundamental problem posed by Yanai at the design phase of the GARP Atlantic Tropical Experiment (GATE) in 1971. The various contributions of Michio Yanai to the current understanding of the dynamics of the tropical atmosphere are briefly reviewed to show how his work has led to several current theories in this field.

1. Introduction

Professor Michio Yanai, who referred to himself as a "meteorological freak" since he was a junior high school student, started his career as a scientist with a study of the genesis of Typhoon Doris from an easterly wave. He recalled that Professor Jule Charney was in attendance during his first presentation about typhoon formation during the First International Symposium on Numerical Weather Prediction in Tokyo, held in 1960. Motivated by the fact that numerical simulations of tropical cyclones were having great difficulty in achieving storm genesis, including those efforts by Charney's Massachusetts Institute of Technology (MIT) group, Michio was determined to pursue the observational and theoretical bases for the formation of storms from preexisting equatorial disturbances. This particular problem

had a huge impact on his development as a tropical meteorologist and stimulated his interest in tropical waves, which became a long-lasting focus of his scientific career. After obtaining his Ph.D. on the study of typhoon formation at the University of Tokyo in 1960, Michio was invited to be a research scientist in the Typhoon Research Division in the Meteorological Research Institute at the Japan Meteorological Agency (JMA). His stay at JMA was short, however, since in the following year, Professor Herbert Riehl at Colorado State University invited Michio to become a post-doctoral researcher for 2 years in 1962–64. Of course, Professor Riehl was the leading expert on easterly waves at the time, so this experience undoubtedly further motivated Michio's interests in the study of tropical waves. In 1965, Michio was invited back to the University of Tokyo as associate professor in the Faculty of Science, where he and his student, Taketo Maruyama,

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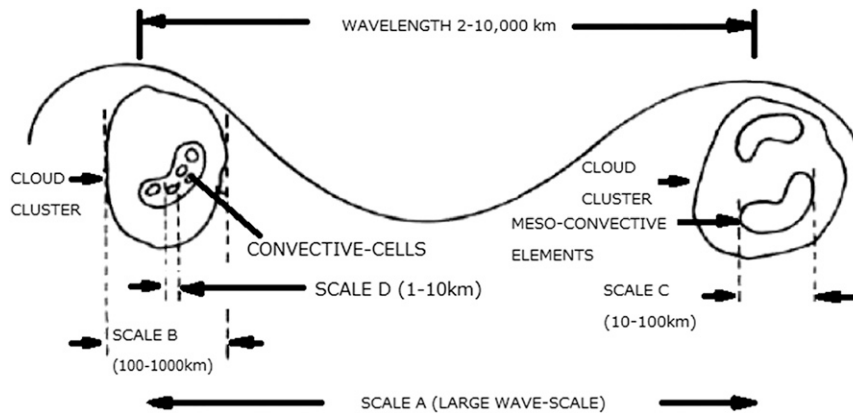


FIG. 3-1. The scales of tropospheric motions in the tropics, taken from the February 1970 GARP technical report. Adopted from Sikdar and Suomi (1971).

documented the existence of mixed Rossby–gravity waves, also called Yanai–Maruyama (YM) waves (see section 3). At that time, the University of Tokyo was strongly affected by student riots, which prompted Michio to accept an invitation by Professor Yale Mintz to join the Department of Meteorology faculty at the University of California, Los Angeles (UCLA), in 1969, where he remained for the rest of his career.

Just 2 years after he moved to UCLA, Michio contributed “A review of recent studies of tropical meteorology relevant to the planning of GATE” (Yanai 1971a) to the International Council for Science (ICSU)–World Meteorological Organization (WMO) Joint Organizing Committee (JOC) for Global Atmospheric Research Program (GARP) where he was appointed as a member of a study group on tropical disturbances. He stated that his primary interests on this subject were “on the A-scale tropical wave disturbances and the interaction of the waves and the B-scale phenomena (cloud clusters).” (Yanai 1971a) During seminars and as part of his tropical meteorology class, Michio often used a schematic such as the one in Fig. 3-1 for representing the multiscale interaction between tropical waves and cumulus ensembles. The nature of the interaction between the cloud scale and the large scale remained a primary focus of Michio’s interest throughout the rest of his career.

It was remarkably prescient that at the design stage of the GARP Atlantic Tropical Experiment (GATE), Michio selected the word “cloud cluster” to refer to a grouping of cumulonimbus, as a key ingredient of tropical waves for scale interactions. One of the major advances of GATE was its field observations that contributed to the understanding of the structure and aggregation of mesoscale systems over the eastern tropical Atlantic (Gamache and Houze 1985; Zipser 1977; Houze and Betts 1981). Another major contribution from Michio’s work during GATE was the analysis of

the mass flux of convection associated with African easterly waves (AEWs). Utilizing the apparent heat source Q_1 and moisture sink Q_2 and a spectral cloud model, Michio and his students (Yanai 1961a, 1971b; Yanai et al. 1973, 1976; Nitta 1977) diagnosed convective mass flux from the soundings (Tao et al. 2016, chapter 2). It was shown that the vertical profiles of convective mass flux in the Atlantic differed from that over the Marshall Islands of the west-central Pacific, with a layered structure of divergence in the middle troposphere in GATE not found in the Marshall Island data. While maximum upward motion is found near 700 hPa in GATE and a secondary maximum is found in the upper troposphere, the only peak found in the western Pacific was at around 400 hPa (Nitta 1977; Yanai and Johnson 1993). Michio’s former graduate student Nitta (1978) further studied the GATE Phase III data to establish the relationships between the structure of the large-scale wave disturbances and cloud height, a key relationship affecting the interaction between the cloud scale and the synoptic scale.

The scale interaction between clouds and waves occupied Michio’s attention for his entire career. In this article, we will revisit Professor Yanai’s contributions to the study of tropical waves and their relationship with tropical convection.

2. Easterly waves and tropical storm genesis

As remarked upon, during the 1960s Michio was heavily involved in both observational and theoretical work related to tropical waves. As his early interests were in typhoons, he was well aware that easterly waves were known to be precursors to tropical storm formation (Riehl 1948; Palmer 1952). As part of his doctoral thesis, Michio studied in detail the 1958 transition of an easterly wave into Typhoon Doris by analyzing Marshall Island special observation data (Yanai 1961a), describing three stages of tropical storm development. He then proceeded

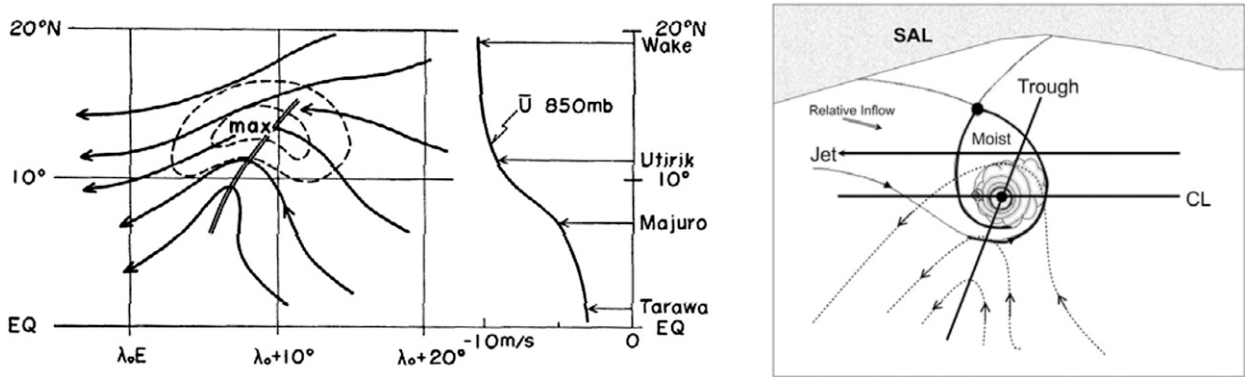


FIG. 3-2. (left) The schematic horizontal view of an easterly wave. Dotted lines are isovels. The latitudinal distribution of mean zonal wind at the 850-hPa level is shown in the right-hand side of the figure. Adopted from Yanai (1961b). (right) A schematic for formation of a tropical storm within a wave pouch. The dashed contours represent the streamlines in the ground-based frame of reference, which usually have an inverted-V pattern. The solid streamlines delineate the wave pouch as viewed in the frame of reference moving at the same speed with the wave. The pouch can protect the mesoscale vortices inside from the hostile environment, such as dry air associated with the Saharan air layer. Deep convection (gray shading) is sustained within the pouch. Owing to convergent flow, the pouch may have an opening that allows the influx of environmental air and vorticity. The easterly jet (Jet), the critical latitude (CL), and the wave trough axis (Trough) are also indicated in the schematic. The intersection of the critical latitude and the trough axis pinpoints the pouch center as the preferred location for tropical cyclogenesis. Adopted from Wang et al. (2010).

to lay out the dynamical basis for such development (Yanai 1961a,b). While this problem is still being worked on today (see Fovell et al. 2016), Michio's ideas on the subject were truly visionary since they clearly spelled out the conditions for the instability of a wave within a moist easterly current and also laid the foundation for the study of the coupling of convection with the large-scale wave field.

In Yanai (1961b, p. 285), Michio first considered the concept, which he attributed to Priestley (1959), of free versus forced convection, with free convection due to buoyancy and forced convection “where the motion is otherwise imposed” by large-scale dynamics, even in a stably stratified atmosphere. The expressions for Q_1 and Q_2 were also first presented in Yanai (1961a). Michio pointed out that the scale of condensational heating initially favored within an easterly wave was much smaller than that of the wave and incipient typhoon themselves but that this heating ultimately must be responsible for the generation of a warm-core protovortex within the initially cold-core easterly wave. This then enabled the rapid deepening of the system (Yanai 1963, 1964). He also remarked in Yanai (1961b, p. 303) that “the banana-shaped storm region associated with an easterly wave appears to be cut off from the main easterly jet” (see Fig. 3-2), perhaps the first hint of the easterly wave “pouch” concept where developing mesoscale vortices are protected from the external hostile environment, allowing development (Dunkerton et al. 2009; Wang et al. 2010).

Throughout the 1960s, Michio was thinking not only about the genesis of tropical storms but also about the genesis of the other equatorial disturbances that were

becoming more evident in observational data. Nitta and Yanai (1969) suggested that the disturbances observed in rainfall in the Marshall Islands (9.00°N, 168.00°E) region were due to the barotropic instability of the easterly zonal current found in the vicinity of the ITCZ. This conclusion found support in later work (e.g., Ferreira and Schubert 1997; Wang and Magnusdottir 2005), while other hypotheses include the roles of baroclinicity aided by convectively generated potential vorticity and/or inertial instability either of the pure kind or along isentropes, concepts that have still recently been pursued as explanations for easterly wave generation (e.g., Tomas and Webster 1997; Toma and Webster 2010). Michio's earliest work thus provided a solid foundation for the idea of large-scale hydrodynamic instability within the ITCZ and provided inspiration for much of the research on equatorial waves and tropical storm development over the following decades to the present.

3. Yanai–Maruyama waves

In the mid-1960s, Michio and his graduate student Taketo Maruyama set out on a search for observational evidence of equatorial disturbances in the central equatorial Pacific using the Marshall Islands data. In this study, they “indeed found interesting facts” corresponding to eddy disturbances in the lower stratospheric winds (Yanai and Maruyama 1966, p. 291). What they found were roughly 5-day-period meridional wind oscillations in the lower stratosphere corresponding to waves traveling westward at around 23 m s^{-1} with a wavelength of 10 000 km or so (Fig. 3-3).

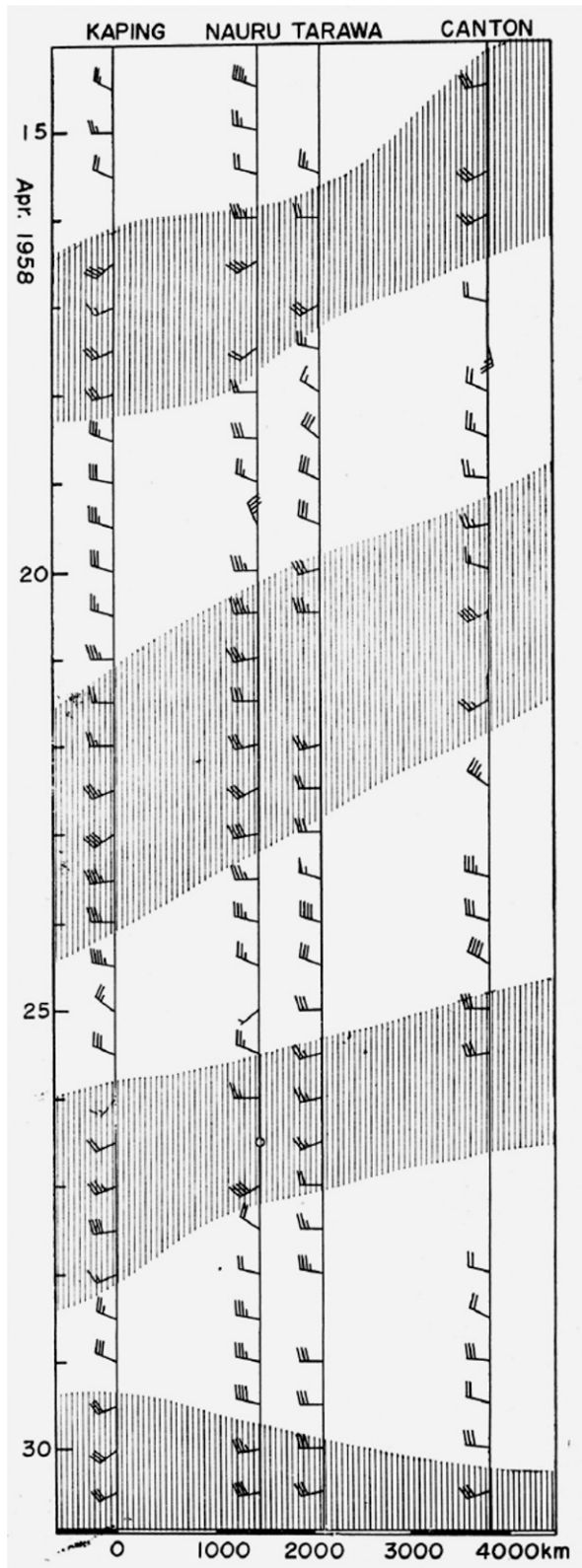


FIG. 3-3. Time series of 70 000-ft (or 21 km) winds at Kapingamarangi, Nauru, Tarawa, and Canton Island for 15–30 Apr 1958. Winds with southerly components are shaded. Adopted from Yanai and Maruyama (1966).

Over the next several years, Michio along with his students Maruyama, Tsuyoshi Nitta, Masato Murakami, and Yoshikazu Hayashi published a classic series of papers documenting these YM waves in observations and theoretically.

It is interesting to note that Yanai and Maruyama's (Yanai and Maruyama 1966; Maruyama and Yanai 1967; Maruyama 1967, 1968) initial work was partly motivated by the search for an explanation for the stratospheric quasi-biennial oscillation (QBO), which had been recently discovered by Ebdon (1960) and Reed et al. (1961). It was theorized that the regular downward-propagating signal of alternating westerly and easterly winds of the QBO should be due to momentum flux convergence produced by equatorial waves (Reed 1962; Tucker 1968). Yanai and Maruyama (1966, p. 291) were also motivated by the fact that "one still lacks observational evidence of large-scale eddies in the tropical stratosphere." While YM waves were presumed to provide part of the necessary acceleration, it is now known that a broad spectrum of forcing must be involved ranging from equatorial waves (Lindzen and Matsuno 1968; Lindzen and Holton 1968; Holton and Lindzen 1972), including intermediate inertia-gravity waves (Dunkerton 1997; Kawatani et al. 2009) and high-frequency gravity waves [see Baldwin et al. (2001) for a review].

At the same time, during the early 1960s, theoretical studies had suggested the existence of a broad class of trapped waves along the equator in addition to off-equatorial easterly waves (Yoshida 1959; Rosenthal 1960, 1965; Bretherton 1964). It was very fortunate that Michio was working "elbow to elbow" with Taroh Matsuno at the University of Tokyo, who was developing the linear theory of the behavior of shallow-water waves on an equatorial beta plane for his Ph.D. work. Matsuno's (1966) theory predicted the existence of several types of equatorially trapped waves, including those now called Kelvin and equatorial Rossby (ER) waves, along with a family of inertia-gravity (IG) and mixed Rossby-gravity (MRG) waves.

Although Michio was acknowledged by Matsuno in his 1966 paper, they apparently did not initially realize that the YM waves provided the first observational confirmation of Matsuno's theory. Quite soon afterward, though, Maruyama (1967, p. 405) examined the observations further and declared that the waves they were observing were indeed "of the mixed characteristics of the Rossby-type wave and the westward moving inertia-gravity wave" isolated by Rosenthal and Matsuno theoretically. This discovery was certainly a beautiful example of where theory and observations worked hand in hand to make rapid advances in a field.

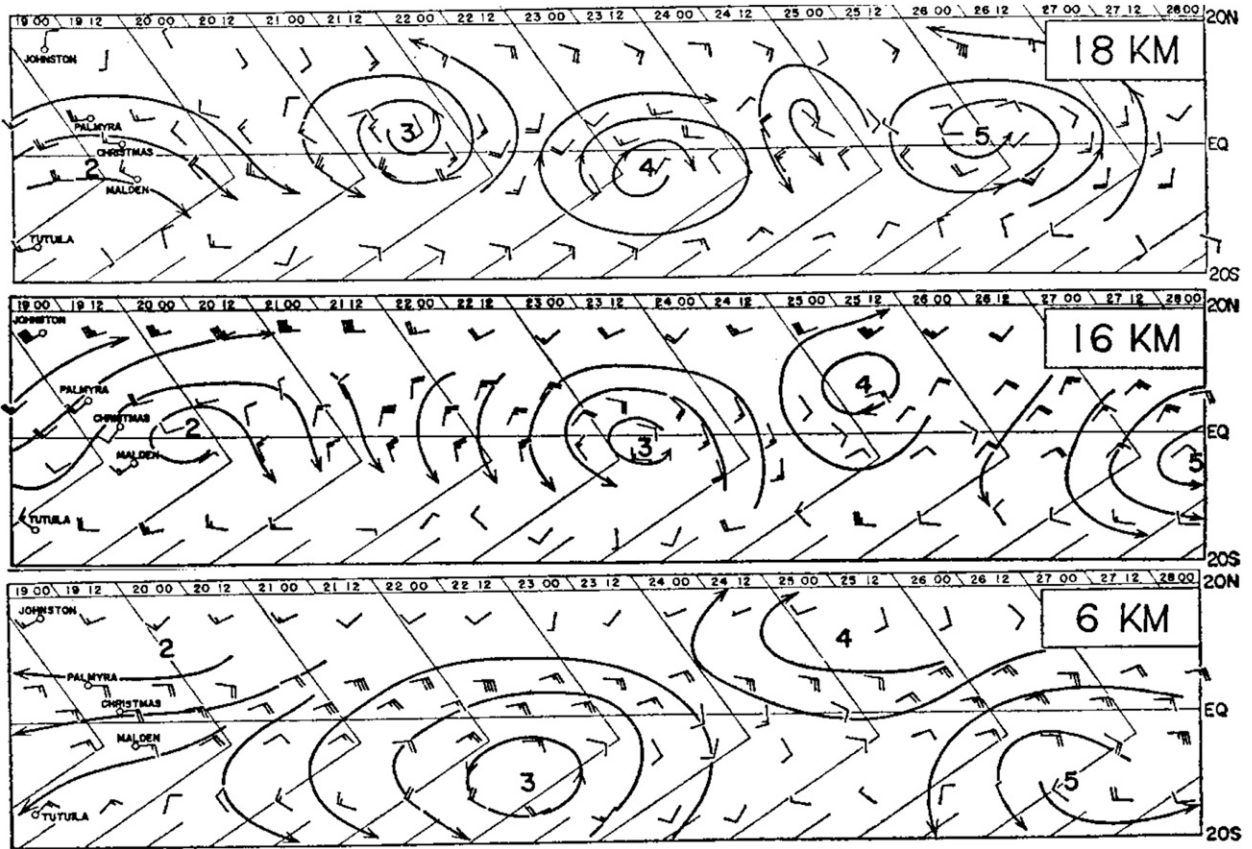


FIG. 3-4. Latitude–time sections of winds at 6, 16, and 18 km in the vicinity of the Line Islands during the period 19 to 27 Jun. The odd and even numerals denote the centers of anticlockwise and clockwise eddies, respectively. Adopted from [Yanai and Hayashi \(1969\)](#).

Further work in the 1960s concentrated on isolating the horizontal structure of YM waves, and their vertical structure, through spectral analysis case studies of data from a wider array of radiosonde sites ([Yanai et al. 1968](#); [Yanai and Hayashi 1969](#); [Wallace and Chang 1969](#); [Yanai and Murakami 1970a,b](#)). These studies confirmed that YM waves consisted of eddies with geopotential perturbations centered along the equator with signals being strongest in the upper troposphere ([Fig. 3-4](#)). However, coherent signals of the YM waves also appeared to be present near the surface ([Fig. 3-5](#); see [section 5](#)). It is notable that in all of these papers there is ongoing speculation that while one energy source for the waves is likely to be latent heating, “there is another possibility of searching for the energy source of the equatorial disturbances in the interaction with higher-latitude disturbances. The low coherence between the equatorial disturbances and those in the subtropics does not necessarily reject a possible impulsive excitation of the equatorial atmosphere by disturbances extending from the subtropics” ([Yanai et al. 1968](#), p. 321). This idea was given further justification

by the two-level model study of [Mak \(1969\)](#), who found a potentially large excitation of YM and ER waves through a realistic lateral forcing at 30°N and 30°S. As we shall see below, the idea of lateral forcing does seem to be quite relevant for a variety of equatorial disturbances.

4. Theoretical developments on equatorial waves

Along with YM waves, observational evidence for other modes predicted by Matsuno’s theory was accumulating quickly by 1970. [Wallace and Kousky \(1968\)](#) documented zonal wind fluctuations in the lower stratosphere using radiosonde data that they identified as Kelvin waves. [Yanai et al. \(1968\)](#), [Yanai and Hayashi \(1969\)](#), and [Yanai and Murakami \(1970a,b\)](#) expanded the spectral analysis approach to a wider range of frequencies and included zonal wind fluctuations and made use of the theoretical expectation that, in a resting basic state, Matsuno modes should have either symmetric or antisymmetric structures about the equator, a common practice today.

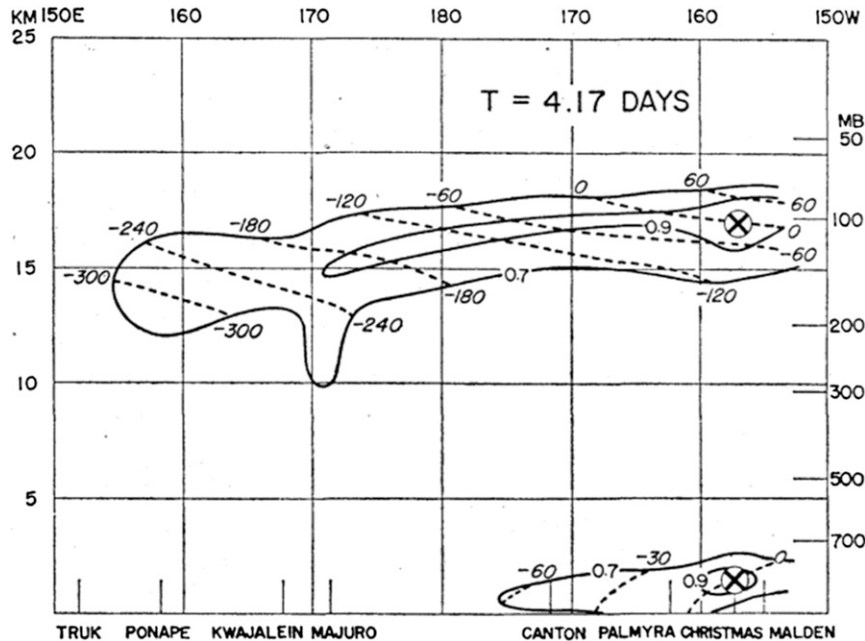


FIG. 3-5. Longitude–height cross section of the coherence (solid lines) and the phase difference (dashed lines) of the v component measured from the 17-km level at Christmas and those measured from the 1.5-km level for the period of 4.17 days. Adopted from Yanai et al. (1968).

As summarized by Wallace (1971), there had been much work done up to this point utilizing spectral approaches developed by Yanai and collaborators. These papers verified many of the predictions of the extensions and applications to Matsuno's theory that were being rapidly developed at that exciting time. For example, Yanai and Murakami (1970b) attempted to account for the scale of the waves using dry, linear theory established by Lindzen (1967) for an isothermal atmosphere, with good results for the YM waves but rather mixed results for Kelvin and ER waves because of the small sample size and low horizontal resolution. Their estimate of an equivalent depth of 41 m, based on the vertical wavelengths for YM waves, was very close to later estimates using satellite cloudiness data (Takayabu 1994a; Wheeler and Kiladis 1999). This is a relatively small value given the observed stratification of the tropical atmosphere (Lindzen 1967; Holton 1970); however, this discrepancy was not commented upon immediately. At around the same time, Hayashi (1971) had incorporated for the effect of heating within YM waves using a conditional instability of the second kind (CISK) formulation for the effect of convective heating, which gave reasonable values for an equivalent depth and for the horizontal scaling of the waves. This pioneering work of Michio's student, along with that of Yamasaki (1969), ultimately led to the formulation of so-called wave-CISK (see Lindzen 1974). It turns out

that the mechanisms that result in such scaling of convectively coupled waves, which undoubtedly arise through the interaction between the convective scale and the large scale, have remained a topic of active research since the 1960s (Neelin and Held 1987) [see discussions in Takayabu (1994a), Wheeler and Kiladis (1999), Kiladis et al. (2009), and Raymond et al. (2009)].

Another result that came out of the pioneering studies of Michio and his collaborators was the evidence that observed equatorial waves exhibited strong tilts in the vertical. A westward tilt with height in the upper troposphere and lower stratosphere was well established for YM waves, and a careful analysis by Yanai et al. (1968) and Nitta (1970a) indicated an eastward tilt within the lower troposphere. Michio pointed out that these tilts suggest that the waves "are excited at the upper tropospheric levels and their wave energy propagates both upward and downward from the excitation levels" (Yanai and Murakami 1970b, p. 345). This was further evidence that, once excited, latent heating within tropical convection was an important energy source for the growth and maintenance of the waves. Michio was particularly impressed with the results of Nitta (1972), who calculated cross spectra in the vertical between Q_1 and the generation of eddy available potential energy (EAPE), finding strong coherence between them at periods near 5 (from YM waves) and 12.5 days (Kelvin

waves). Michio commented on the implications for the role of convection: “It is very interesting that the two diagrams are nearly identical, that is, at all frequency ranges the EAPE is generated by diabatic heating and is immediately converted into the EKE [eddy kinetic energy]” (Yanai 1971a, p. 10).

In another prescient statement, Yanai and Murakami (1970a) saw the need for more detailed space–time spectral analysis techniques, which were then in fact being developed by Michio’s student Yoshikazu Hayashi (Hayashi 1971). They realized that when enough data became available “to establish a physical interpretation of the time series data, we have to analyze the spectral estimates into different wave modes in a manner similar to the analysis of atmospheric tides” (Yanai and Murakami 1970a, p. 196) as was done, for example, by Longuet-Higgins (1968). This statement foresaw the matching of theoretical dispersion properties of equatorial waves to space–time characteristics of observed fields.

5. Convection and equatorial waves

At around 1970, the motivation to study equatorial waves was further reinforced by some initial work using satellite data. Michio was struck by the work of Chang (1970), who showed an association between tropical wave disturbances and cloud cluster activity (Fig. 3-6). Shortly thereafter, Tanaka and Ryuguji (1971, 1973), Murakami and Ho (1972a,b), and Wallace and Chang (1972), among others, found strong evidence for equatorial wave activity in satellite cloudiness, using some of the first available observations from the *TIROS-I* satellite. The importance of easterly waves for determining the organization of precipitation within the tropics was already long recognized, and Michio and others saw the potential for other equatorial modes to also impact rainfall. The important advance that satellite data offered made it even more relevant to establish the nature of the convective coupling to wave dynamics at low latitudes.

Michio’s efforts to understand the relationships between wave and convective activity within the theoretical framework of Matsuno’s theory were aided by the arrival of his first Ph.D. student at UCLA, Abraham Zangvil. Zangvil and Yanai (1980, 1981) analyzed the space–time spectra of dynamical and brightness temperature fields using one of the first gridded analysis fields of the tropics produced by Krishnamurti (1971) and a gridded satellite brightness temperature product obtained from NCAR. The use of a grid instead of spotty radiosonde data made it possible to decompose the fields into wavenumber–frequency space, and they

found clear evidence of cloudiness variations coupled to YM, Kelvin, and ER waves and strong coherence between cloudiness and their dynamical fields. Another outgrowth of the work with Zangvil was further evidence confirming the previous findings of Nitta and others, for the equatorward flux of wave energy of zonal wavenumbers 3–6, matching the scale of YM waves (Fig. 3-7).

The early evidence gathered by Yanai and collaborators on equatorial waves provided inspiration for much of the tropical research in the late 1980s and 1990s. An eastward-propagating mode responsible for the large-scale organization of cloud clusters, called super cloud clusters (SCC) by Nakazawa (1988), was later determined to be coupled with tropospheric Kelvin wave disturbances by Takayabu and Murakami (1991) and Takayabu et al. (1999). Liebmann and Hendon (1990) and Hendon and Liebmann (1991) also demonstrated the coupling of tropospheric YM waves and cloudiness utilizing gridded ECMWF wind analyses and outgoing longwave radiation (OLR) data and confirmed the tilted vertical structures and scales of the waves that were isolated in the more limited early observations of Yanai.

Further study revealed a rich variety in YM waves ranging from those coupled to convection to the free waves of the upper troposphere and lower stratosphere. Dunkerton (1991) analyzed radiosonde data from a large set of equatorial stations and found that lower-stratospheric YM waves at 70 hPa tended to appear episodically as localized wave packets and were characterized by a broad range of phase speeds. Similar results were obtained by Randel (1992) but for longer-period (6–10 day) upper-tropospheric YM waves over the eastern Pacific/South America sectors, which were uncoupled to convection and determined to be quite distinct from those over the west Pacific warm pool. Randel (1992) also found strong evidence for extratropical forcing of the wave activity, with wave activity coincident with meridional momentum fluxes from the Southern Hemisphere subtropics. Dunkerton (1993) and Dunkerton and Baldwin (1995) documented the detailed vertical structure of YM and easterly waves in station as well as gridded OLR and ECMWF analyses. Apart from the lower-stratospheric waves, these studies again inferred a broad range of scales associated with tropospheric YM waves, with at least two types of waves of identified. One of these appeared to be uncoupled to convection and more prevalent in the upper troposphere, as were the YM waves studied by Randel (1992), while the other appeared to be more convectively coupled and had maximum amplitude in the lower troposphere.

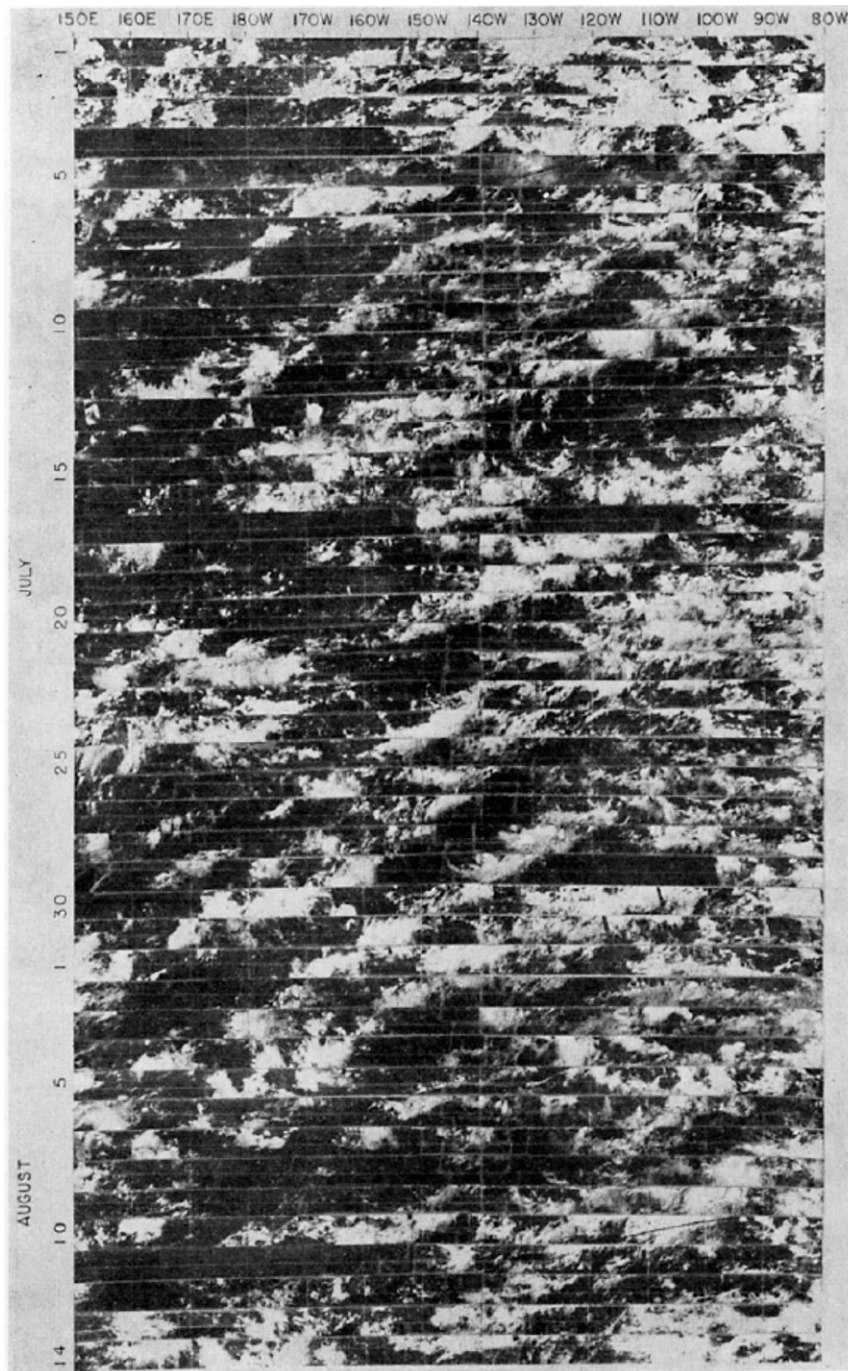


FIG. 3-6. Time-longitude section of satellite photographs of the period 1 Jul–14 Aug 1967 for the 10° – 5° N latitude band in Pacific. The following data are missing: 4 Jul (150° E– 155° W), 8 Jul (150° E– 160° W), 7 Jul (150° E– 150° W, 130° – 100° W), 29 Jul (130° – 100° W), and 11 Aug (150° E– 150° W). Adopted from [Chang \(1970\)](#).

As more complete gridded satellite and dynamical analyses were quickly becoming available in the 1980s, the work of [Zangvil and Yanai \(1980, 1981\)](#) helped to lay the groundwork for the application of [Hayashi's \(1971\)](#)

space-time spectral techniques to gridded satellite and meteorological analyses based on satellite and rawinsonde data. [Yanai and Lu \(1983\)](#) documented the existence of Kelvin, YM, and ER waves in the equatorial

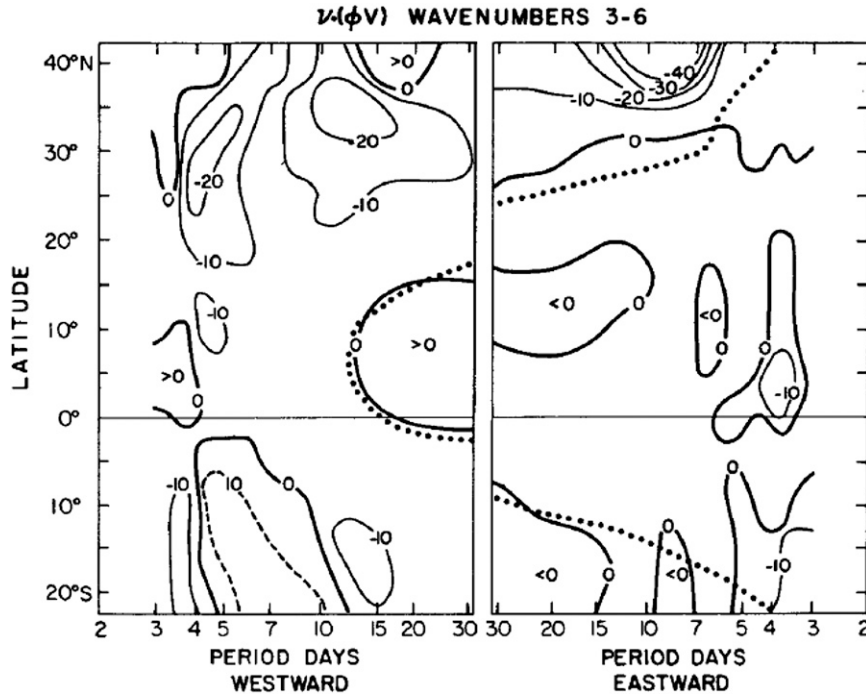


FIG. 3-7. Latitude–frequency section of the meridional flux of wave energy multiplied by frequency (positive northward) for $s = 3\text{--}6$ ($\text{m}^3 \text{s}^{-3}$). Adopted from Zangvil and Yanai (1980).

upper troposphere and related their variability to variations in the equatorward flux of wave energy through the subtropics (see section 6). Takayabu (1994a) plotted the space–time spectral power of satellite brightness temperature in a wavenumber–frequency diagram averaged over latitude, in addition to the more commonly used wavenumber–latitude diagram for a given wavenumber range. These spectra were then directly comparable to dispersion relationships derived by Matsuno, and a wide variety of equatorial waves were revealed including Kelvin, YM, ER, easterly waves [tropical depression (TD) type], and various species of inertio-gravity waves (Fig. 3-8). It was also confirmed that the equivalent depth of these waves indeed corresponded to relatively shallow values of around 15–30 m. A similar application was taken to look specifically at westward inertio-gravity (WIG) waves (Takayabu 1994b). These studies created the impetus for further application of space–time spectral approaches and enabled the development of objective techniques to filter for convectively coupled equatorial waves (CCEWs) (Fig. 3-9; Wheeler and Kiladis 1999). The motivation for much of the more recent work on convectively coupled equatorial waves (Yang et al. 2007; Kiladis et al. 2009; Chen and Tam 2012) and the MJO (see Maloney and Zhang 2016) can indeed be traced back to Michio’s long standing interest in the relationship between convection

and the large-scale flow field and to the analysis techniques developed over the years as a result of his huge influence.

6. Extratropical forcing of equatorial waves

Based on a scale analysis, Charney (1963) was among the first to hypothesize that a large portion of the equatorial circulation could be forced by extratropical circulations. Charney (1969) then went on to reason that, in the presence of a realistic zonal-mean basic state, extratropical waves might be prevented from penetrating into the tropics through the existence of a critical line, where the zonal phase speed of an equatorward-propagating disturbance matched the background zonal wind speed (see also Charney and Drazin 1961). It was further argued that, in the absence of convection, such disturbances would be difficult to couple in the vertical once they reached lower latitudes. Charney cited Michio’s spectral analysis of Pacific meridional wind (Yanai et al. 1968), which found distinctly different time scales between the lower and upper equatorial troposphere, as evidence of the relatively weak coupling in the vertical of dry tropical motions.

However, Nitta (1970a,b, 1972) demonstrated a lateral flux of wave energy into the tropics from the extratropics in the upper troposphere, and later theoretical

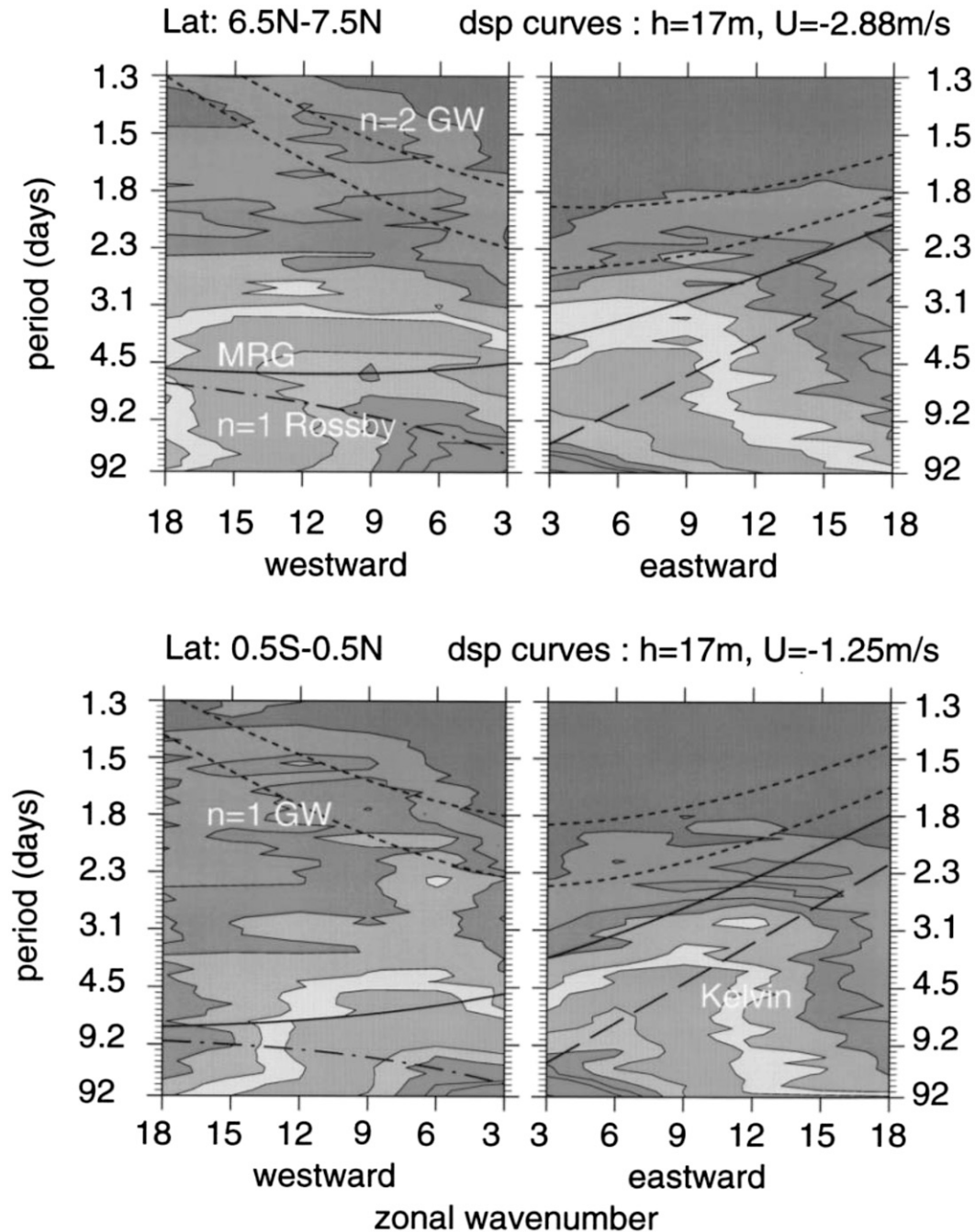


FIG. 3-8. Wavenumber–frequency distribution of space–time power spectral density along the equatorial latitude of (a) 0.5°N – 0.5°S and (b) 6.5° – 7.5°N . Spectral values are averaged for the entire period from 1981 to 1989, except for 1984. Contours are plotted for 5.3, 7.9, 10.5, 15.7, 21.0, 42.0, 63.0, 84.0, and $105.0 \times 10^{12} \text{ K}^2 \text{ s m}$. Doppler shifted dispersion curves of equatorial waves for $n = -1, 0$, and 1 modes and $n = 2$ inertio-gravity wave mode are superimposed. (Long dashed line indicates Kelvin wave, solid line is MRG, short dashed line is $n = 1, 2$ IGW, and dashed-dotted line is $n = 1$ Rossby wave.) Adopted from Takayabu (1994a).

and modeling work provided evidence that lateral forcing from the extratropics should be possible, and indeed prevalent, in regions of sufficiently broad-scale upper-level westerly flow at low latitudes (e.g., Webster

and Holton 1982; Itoh and Ghil 1988; Zhang and Webster 1992). These regions, termed westerly ducts, present no critical line to the equatorward propagation of quasi-stationary Rossby wave energy (Webster and

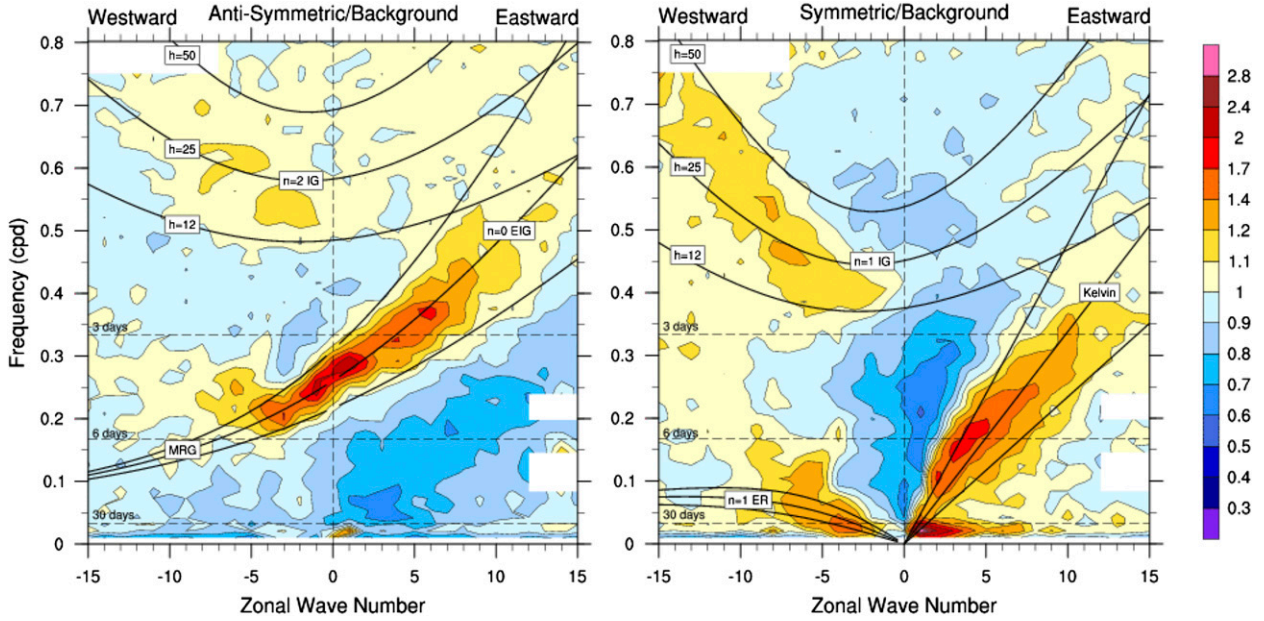


FIG. 3-9. (a) The antisymmetric OLR power divided by the background power. Superimposed are the dispersion curves of the even meridional mode-numbered equatorial waves for the three equivalent depths of $h = 12, 25$, and 50 m. (b) As in (a), but for the symmetric component of OLR and the corresponding odd meridional mode-numbered equatorial waves. Frequency spectral bandwidth is $1/96$ cpd. Adopted from [Wheeler and Kiladis \(1999\)](#).

[Holton 1982](#)). For example, [Fig. 3-10](#) shows the perturbation zonal wind generated in a shallow-water model by a forcing situated at 20°N poleward of a westerly duct, with a clear cross-equatorial response.

During the 1980s and 1990s, Michio's group further documented the importance of lateral forcing as a triggering mechanism for equatorially trapped waves. [Zangvil and Yanai \(1980\)](#) and [Yanai and Lu \(1983\)](#) showed the general patterns of tropical-extratropical interactions that result in Rossby, YM, and Kelvin waves forced by wave energy flux at equatorial latitudes ([Fig. 3-7](#)). In various analyses ([Zangvil and Yanai 1980](#); [Yanai and Lu 1983](#); [Magaña and Yanai 1995](#)), the wave energy flux of long waves ($s = 3-6$) at 200 mb exhibited a dominance of equatorward concentration in the 4–6-day-period range. Numerous theoretical and modeling studies followed up on the idea that this wave energy could trigger equatorial waves (e.g., [Webster and Chang 1988](#); [Itoh and Ghil 1988](#); [Zhang and Webster 1992](#); [Horinouchi et al. 2000](#)).

The importance of lateral forcing led [Magaña and Yanai \(1991\)](#) to explore the possible role of the MJO on the meridional convergence of wave energy flux into the tropics (see [Krishnamurti et al. 2016](#)). They showed how the 30–60-day oscillations in tropical convection over the western Pacific may influence the subtropical circulation over a range of longitudes, which in turn could lead to the formation of the westerly duct even during

the Northern Hemisphere summer months. Utilizing ECMWF analysis data, [Magaña and Yanai \(1995\)](#) documented how a midlatitude Rossby wave train can penetrate deeply into the tropics and project onto YM waves, especially in the western Hemisphere within a sufficiently wide equatorial westerly duct or even when the mean easterlies are weak ($\sim 2 \text{ m s}^{-1}$) ([Fig. 3-11](#)).

Other evidence for lateral forcing of equatorial motions has become quite abundant over the past three

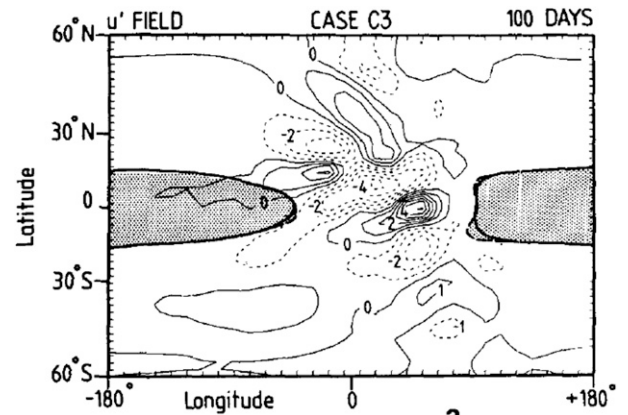


FIG. 3-10. Distribution of the perturbation zonal wind component u' at 100 days for case C3 that considers an $s = 3$ forcing with $\phi = 0$ located at 20°N with basic state C. Adopted from [Webster and Holton \(1982\)](#).

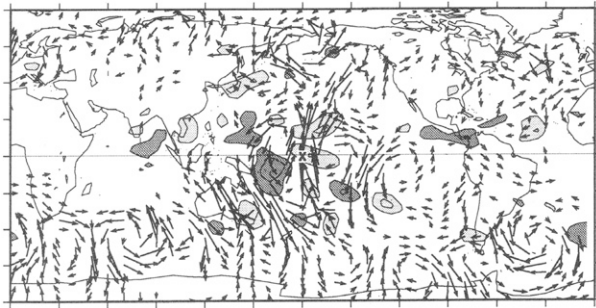


FIG. 3-11. Linear regression between the bandpass-filtered anomalies of v at the reference point x and bandpass-filtered u , v , and OLR anomalies at all points. Dark (light) shaded regions correspond to negative (positive) OLR anomalies. Contour intervals for OLR anomalies: 4 W m^{-2} . Only wind vectors with magnitudes larger than 0.8 m s^{-1} are plotted. For periods of active MRGs. Adopted from Magaña and Yanai (1995).

decades in synoptic-scale studies. For example, Kiladis and Weickmann (1992) demonstrated that extratropical Rossby wave energy propagating equatorward within the westerly duct of the eastern Pacific was responsible for convective activity within the ITCZ. Tomas and Webster (1994) showed that such disturbances could efficiently cross the equator at upper levels but are hindered at low levels by the critical line of the so-called easterly dome due to the trade winds. Similar equatorward wave propagation is also seen in the Atlantic sector, where equatorial westerlies are also present during northern winter. The interaction of this wave activity with the ITCZ is now well established [see the review by Knippertz (2007)].

There is also observational evidence that ER waves can be triggered by extratropical waves penetrating into low latitudes (Yanai and Lu 1983; Kiladis and Wheeler 1995; Kiladis 1998). More recently, Straub and Kiladis (2003) and Liebmann et al. (2009) present evidence of laterally forced equatorial Kelvin waves. For example, in Fig. 3-12, a convectively coupled Kelvin wave signal originating over the west Pacific warm pool is preceded by an extratropical Rossby wave train originating many days earlier over South America and propagating through the southern Indian Ocean storm track. It is especially notable that this wave train is very similar to the one associated with YM waves in Fig. 3-11. These events frequently occur even in the presence of a critical line, and it has been hypothesized that the high-latitude forcing can project directly onto the equatorial wave, yielding an equatorial response in either easterly or westerly low-latitude flow (e.g., Hoskins and Yang 2000). Thus, the early insightful observations of Michio and his collaborators, such as Nitta, that indicated excitation

of equatorial modes by lateral forcing have since been verified since by many studies, highlighting the important role of this source of equatorial wave variability, as was suspected early on by Michio.

7. Revisiting the classical easterly and equatorial waves

In preceding sections, we have reviewed the work on tropical waves where Michio had tremendous contributions. Various studies over the years have revealed that there are different mechanisms responsible for generating or maintaining tropical waves. Off-equatorial 3–5-day gyres traveling along the Atlantic ITCZ may be considered to be classical easterly waves, as these were the first to be described in detail using the Caribbean rawinsonde and surface network (Riehl 1945). Later, atmospheric wave disturbances very similar to Caribbean easterly waves were found in the central to western equatorial Pacific, utilizing the radiosonde network around the Marshall Islands (Palmer 1952). In Palmer (1952), these disturbances were called equatorial waves, since those waves were found closer to the equator, although their characteristics were described as very similar to easterly waves. In the 1960s, the distinction between equatorial waves and easterly waves was generally not very clear (e.g., Nitta and Yanai 1969), mainly because of the similarity of their periodicity and their coexistence as will be described later. However, Michio was careful about the distinction between them in papers (e.g., Yanai et al. 1968). In this section, we revisit these classical easterly waves and their relationship to equatorial waves, and YM waves in particular, through accumulated studies on tropical wave disturbances.

One of the first ideas for the generation mechanism was due to Palmer (1951), who speculated that easterly waves could be maintained through the horizontal shear within an easterly current. Later, Michio pursued the possibility of the generation of easterly waves in the Marshall Island region from barotropic instability (Nitta and Yanai 1969), based on a careful application of the finite differencing approximation (Yanai and Nitta 1968), and showed that the meridional structure of easterly flow in this region could become barotropically unstable, providing one potential source for easterly wave generation with observed spatial scales and propagation speeds.

At the time of GATE, similar arguments were put forth to account for the origin and maintenance of AEWs. Burpee (1972) argued that the African easterly jet satisfied the Charney–Stern condition for barotropic instability (Charney and Stern 1962). Based on the GATE analyses, a consensus was established that

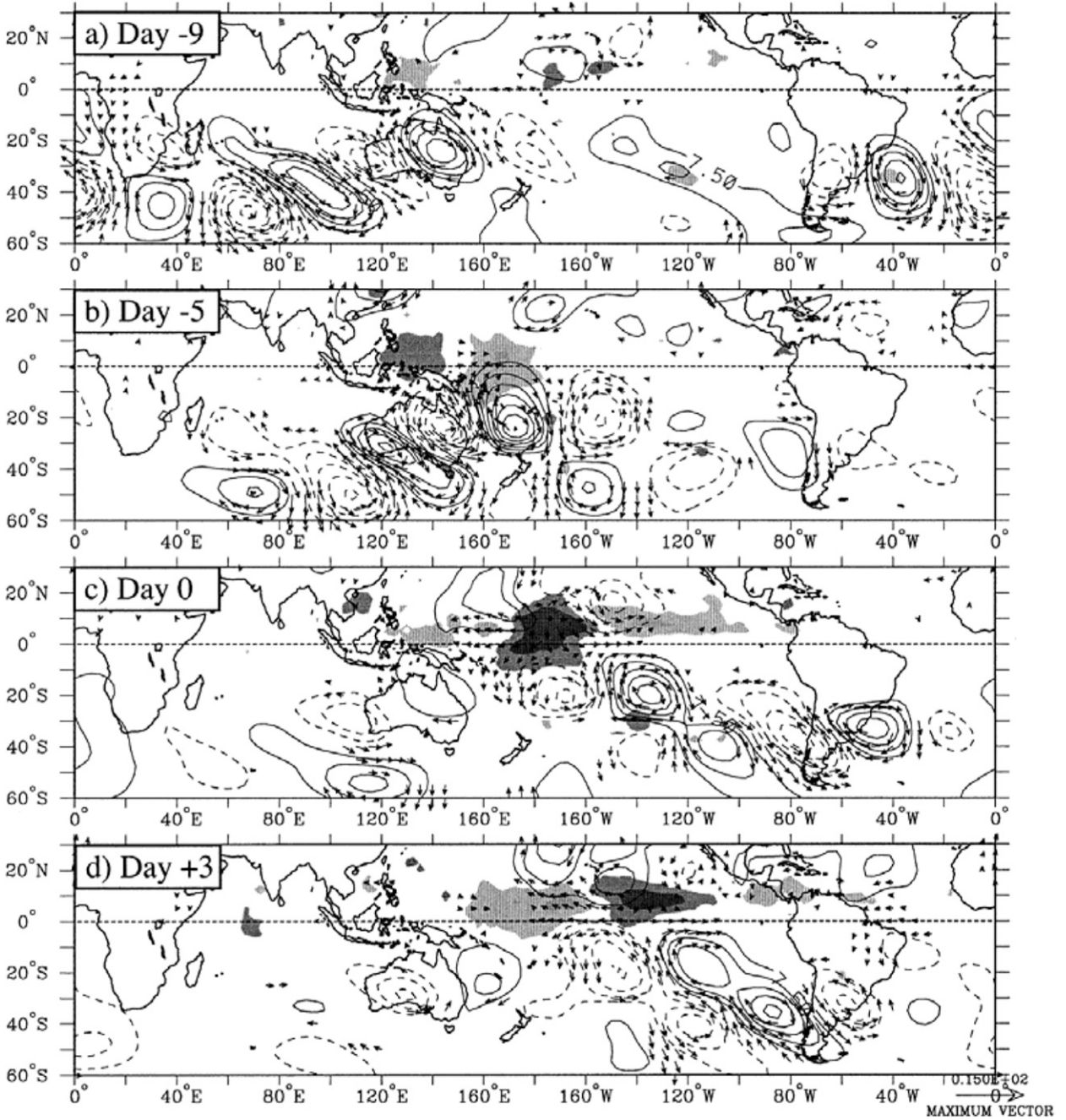


FIG. 3-12. Regressed values of OLR (shading) and 200-hPa streamfunction (contours) and winds (vectors), based on a -40 W m^{-2} anomaly in Kelvin wave filter OLR at the base point on day 0, for (a) day -9, (b) day -5, (c) day 0, and (d) day +3. OLR is shaded at ± 6 and 15 W m^{-2} ; dark shading represents negative OLR anomalies. Stream function contour interval is $7.5 \times 10^5 \text{ m}^2 \text{ s}^{-1}$; the zero contour has been omitted. The longest wind vectors correspond to a 10 m s^{-1} wind, and are plotted only where either the u or v component is significant at the 95% level or greater. Adopted from [Straub and Kiladis \(2003\)](#).

AEWs were dynamically maintained with barotropic and baroclinic conversions from the lower-tropospheric easterly jet (e.g., [Norquist et al. 1977](#); [Reed et al. 1977](#)). However, it appears that linear instability is not necessarily supported by realistic observed basic states over

Africa once reasonable damping is assumed (see [Hall et al. 2006](#)), pointing to a role by moist processes in the triggering of AEWs ([Thorncroft et al. 2008](#)) as well as their maintenance (e.g., [Hsieh and Cook 2008](#); [Cornforth et al. 2009](#); [Berry and Thorncroft 2012](#)).

On the other hand, tropical waves observed over the Marshall Islands, around 150° – 175° E, were shown to be maintained primarily by deep convection (Nitta 1972), consistent with the view that there is less horizontal and vertical shear over the western to central Pacific than over Africa. Similarly for the convectively coupled equatorial waves, convective heating in organized convective systems, which consists of deep convection and deep stratiform clouds, is considered the major player in the maintenance of these disturbances.¹

Differences in the structure of easterly waves from the eastern Pacific to the western Pacific had long been recognized starting with Reed and Recker (1971), who showed the structure change of easterly waves from the central Pacific at Majuro to the western Pacific at Koror and Truk. In the central Pacific, the disturbances have more eastward-tilted structure than in the western Pacific, where the disturbances are more erect, as noted by Dunkerton (1993; see also Serra et al. 2008).

In addition to the vertical structure, early studies with station data (e.g., Nitta 1970a,b; Yanai and Murakami 1970a,b; Wallace 1971) suggested the existence of two kinds of westward-propagating waves. Nitta (1970a) showed that while longer (~ 8000 km) waves dominate over the central Pacific, shorter (~ 4000 km) waves dominate over the western Pacific. Liebmann and Hendon's (1990) work visually indicated that former wave disturbance had a YM (MRG) wave structure and was coupled with convection. Takayabu and Nitta (1993) identified the TD-type disturbances that corresponded more with easterly waves and dominated in the western Pacific, distinct from the MRG wave in the central Pacific, although they indicated some cases that the former disturbance was transformed from the latter. One of the conclusions that emerged from Dunkerton and Baldwin (1995) was that some MRG waves in the central to western Pacific appear to transition

¹ More recently, the role of a third type of cloud, shallow/congestus, has been emphasized (Johnson et al. 1999). Usually, these clouds are assumed to play a primary role in moistening the lower troposphere above the boundary layer ahead of convectively coupled disturbances, although there is some dispute on this point (Hohenegger and Stevens 2013). Kiladis et al. (2005) and Mapes et al. (2006) remarked on the fact that a wide variety of cloud systems with different scales have similar life cycles, consisting of a progression of shallow/congestus, deep, and stratiform clouds as they pass by (e.g., Zipser 1969; Takayabu et al. 1996; Straub and Kiladis 2003; Lin and Johnson 1996). Frenkel et al. (2012) showed that realistic structures of various cloud systems are well simulated by stochastic cloud models, including the effects of the three cloud types, as demonstrated by Majda and Khouider (2002) and Khouider and Majda (2006) (see Fovell et al. 2016; Zhang and Song 2016).

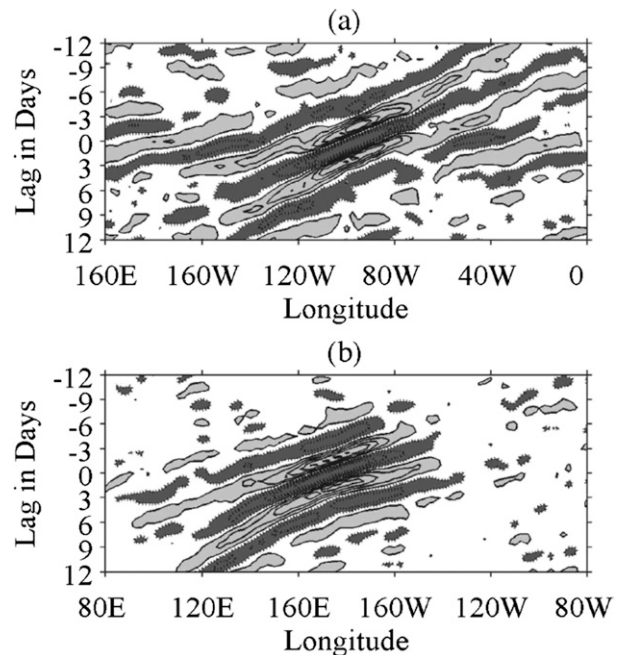


FIG. 3-13. Hovmoeller diagram of TD-filtered OLR regressions averaged from 7.5° to 12.5° N for the base points at (a) 10° N, 95° W and (b) 7.5° N, 172.5° E. Dark gray contours are negative anomalies; lighter gray contours are positive anomalies. Contour lines are drawn at intervals of 2 W m^{-2} starting at $\pm 1 \text{ W m}^{-2}$. Adopted from Serra et al. (2008).

continuously into the TD-type disturbances. This result corroborated earlier work by Dunkerton (1993) from rawinsonde data alone, that showed evidence of a continuous transition from a tilted to a first baroclinic mode vertical structure of disturbances.

The relative occurrence of MRG waves and TD-type disturbances depends on the background zonal wind structure over the tropical Pacific with MRG waves favored in low-level easterlies and TDs favored in westerlies. Takayabu and Nitta (1993) found such an interannual variation associated with ENSO. Recalling that there are at least some inconsistencies in earlier studies for the naming of the 3–5-day disturbances over the Marshall Island region (e.g., Palmer 1952 versus Nitta and Yanai 1969), some of these discrepancies may have their origin due to this interannual variability.

Studies of easterly waves in the eastern Pacific ITCZ are more prevalent in more recent years, which was partly due to the lack of a rawinsonde station network in this region. In agreement with classical studies dating at least to 1970, Serra et al. (2008, 2010) showed that some easterly waves originating in the Atlantic propagate across Costa Rica and Panama to the eastern Pacific (Fig. 3-13), although they are not the primary origin of Pacific disturbances. In the eastern Pacific at around

80°–95°W, they show that barotropic conversion has similar magnitudes in the lower troposphere as the contribution from convection.

The eastern Pacific ITCZ region is characterized by more prevalent contributions by shallow convection to the heating profile when compared to the western Pacific warm pool region, as illuminated by recent studies. Zhang et al. (2004) indicated the existence of a shallow meridional circulation in the eastern Pacific at around 2–4-km altitude, utilizing dropsonde soundings obtained in the Eastern Pacific Investigation of Climate Processes in the Coupled Ocean–Atmosphere System (EPIC) program. Kubar et al. (2007) showed a larger ratio of midlevel-topped clouds in the eastern Pacific compared to the western or central Pacific. Back and Bretherton (2009a,b) emphasized the significance of a shallow mode of convection in the eastern Pacific ITCZ region, accompanying convergence in the boundary layer associated with strong SST gradients associated with the so-called cold tongue in the equatorial eastern Pacific. Shallow heating may also be enhancing the low-level convergence through convection–circulation coupling (Wu 2003).

An analysis of TRMM precipitation features (PFs), which are contiguous rain areas defined by the TRMM PR data and are provided by the University of Utah group (e.g., Nesbitt et al. 2006), described significant differences of convective systems between the western Pacific (WPAC) warm pool and over the eastern Pacific (EPAC) ITCZ (Yokoyama and Takayabu 2012a,b). Over the WPAC warm pool, tall and deep structures are prominent. On the other hand, over the EPAC ITCZ, small and shallow features rich in cumulus congestus and highly organized features with moderate heights are dominant, collocated with regions of shallow convergence associated with large meridional SST gradients.

The significant contributions of shallow convection observed in temporally averaged states over the eastern Pacific ITCZ are related to transient atmospheric disturbances. Serra and Houze (2002) analyzed the observational data obtained during the Tropical East Pacific Process Studies (TEPPS). Their time–height plots of sounding data indicate that premoistening below the 0°C level precedes the precipitation events associated with 3–6-day wave disturbances. Roundy and Frank (2004) showed an interesting snapshot of easterly wave disturbances over the central to eastern equatorial Pacific, with a map of TD-type band-filtered precipitable water (PW), OLR, and 850-hPa winds on 7 December 1992. In the map, disturbances are clearly detected in precipitable water signals and associated with an MRG wavelike circulation over the equator.

Utilizing NOAA OLR data, total precipitable water data derived from SSM/I, surface winds from the

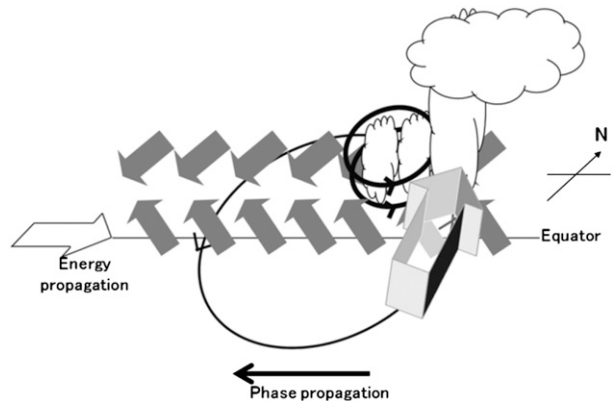


FIG. 3-14. Schematic for the relationships among cumulus convection, the synoptic-scale coupled disturbances, and the large-scale environment over the eastern Pacific in the boreal autumn. Small and large circles indicate a vortex disturbance and a MRG wave-type disturbance, respectively. The thick light gray arrow represents deep convergence associated with the MRG wave-type disturbance. Dark gray arrows indicate shallow convergence, which is largely driven by the strong SST gradient. Black solid and open arrows indicate phase and energy propagation, respectively. Small and large cloud-shaped figures are depicted as congestus and well-organized systems, respectively. Adopted from Yokoyama and Takayabu (2012b).

QuikSCAT, 25-yr Japanese reanalysis, and TRMM latent heating data during the boreal autumn, Yokoyama and Takayabu (2012b) statistically obtained the coupled structure of the ITCZ disturbances over the eastern Pacific centered around 130°W, as summarized in Fig. 3-14. It consists of vortices tilted from SW to NE along the ITCZ latitude, and larger-scale MRG wave disturbances, over the equator. At both these latitudes, westward-propagating 3–6-day disturbances were observed, but the phase speeds and wavelengths of the vertical and MRG wavelike disturbances suggest they have separate origins. Two-tiered convergence–divergence profiles are observed with these coupled disturbances. In the western part of the disturbances, deep convection is suppressed and shallow convection is observed. Much deeper convergence up to 700 hPa is observed in the eastern part, associated with southerly inflow of the MRG waves. This helps to allow deep convection in the rear of the vortex disturbance at the ITCZ and enhances the coupled wave disturbances. When these two components become coupled, they tend to propagate westward together over a period of several days.

Recent studies have revealed that tropical deep convection is more correlated with free-tropospheric humidity rather than buoyancy instability of the shallower boundary layer parcels represented by CAPE (e.g., Sherwood 1999; Bretherton et al. 2004; Takemi et al. 2004; Neggers et al. 2007; Takayabu et al. 2010). The

above-mentioned coupled structure of the ITCZ disturbances show that shallow convection associated with one disturbance is aided by the deep convergence of a large-scale disturbance, which helps to prepare the environment of the moist free troposphere for deep convection to develop.

To summarize, it is suggested that dynamic instability and barotropic conversion in the shallow boundary layer generate and maintain the shallow vortex disturbances in the eastern Pacific ITCZ, which are coupled to convective heating. When conditions allow, associated with the arrival of energy from larger-scale MRG waves, deeper convergence in the lower troposphere allows deep convection in a certain phase of the shallow vortex.

The coupling of shallower and deeper disturbances in the eastern Pacific ITCZ is consistent with previous descriptions of these disturbance structures. While disturbances in the west Pacific have erect structures with a single maximum of vertical velocity in the upper troposphere, AEWs (Thompson et al. 1979; Kiladis et al. 2006) and wave disturbances in the eastern Pacific (Tai and Ogura 1987; Serra et al. 2008; Yokoyama and Takayabu 2012b) are associated with double maxima of vertical velocity in the lower and upper troposphere. With both AEW and classical eastern Pacific easterly waves, there are indications of lower-level barotropic instability triggering the disturbance, which is coupled with shallow convection, especially in the eastern Pacific cases. Then further coupling with deep convection enhances the disturbances with deep convective heating.

From the very early stage of the YM wave studies, Michio was interested in the relationship between upper-level YM waves and the lower-level easterly waves. As was already shown in Fig. 3-5, Yanai et al. (1968) showed a coexistence of long distance propagation of large-scale YM waves from the upper troposphere to lower stratosphere and short distance correlation of wave disturbances in the lower troposphere at around 1.5 km, at a very similar period range around 4 days. Although Michio did not explicitly express that the latter lower-tropospheric coherent disturbances was a part of YM or MRG waves, he suggested that these spectral peaks may correspond to the passage of equatorial waves of the type discussed by Palmer (1952), considering that the latitudes of stations showing these peaks are close to the equator. From Fig. 3-5, the zonal scale of these lower-tropospheric wave disturbances is estimated at wavenumber 4, which is distinct from the smaller-scale easterly waves. Utilizing results from recent studies (Roundy and Frank 2004; Yokoyama and Takayabu 2012b), we can now revisit the equatorial waves described by Palmer (1952), which should correspond to the lower-tropospheric MRG

waves, and distinguish these from the easterly waves over the ITCZ. They can be consistently understood as two disturbances with separate origins, which are coupled and amplified through an enhancement of deep convection over a limited longitudinal range of the eastern Pacific ITCZ. Given the limited data availability available to them, we can certainly appreciate the marvelous insights of early tropical meteorologists in assigning two separate names, easterly waves and equatorial waves, to these disturbances in the early days of the 1950s and 1960s.

Professor Yanai, in his review for the design of GATE, emphasized the importance of understanding multiscale interaction in tropical waves and coupled tropical convection: “Finally, I emphasize that the B-scale network must be meshed within a good A-scale network. Only by doing so, will we be able to associate a particular type of convective heating with a particular type of wave disturbance” (Yanai 1971a, p. 29). Successive studies have shown abundant variations in tropical waves, and the selection of waves has been related to the large-scale basic state. One of the facts initially emphasized by Michio, that the scale of tropical convection was much smaller compared to that of tropical waves, has ultimately led to recent field projects such as the Pre-Depression Investigation of Cloud-Systems in the Tropics (PREDICT) experiment (Montgomery et al. 2012). PREDICT was designed to understand which waves are apt to develop into the tropical cyclones and which are not, in terms of convective effects on the pregenesis disturbances, the very problem studied by Michio in the early 1960s in his papers on the genesis of Typhoon Doris. Another recent field project, Dynamics of the MJO (DYNAMO)/Cooperative Indian Ocean Experiment on Intraseasonal Variability in Year 2011 (CINDY) (e.g., Zhang et al. 2013; Yoneyama et al. 2013), is designed to examine the role of mesoscale to synoptic-scale interactions in the genesis and maintenance of the planetary-scale MJO (see Krishnamurti et al. 2016). Thus, Michio’s insightful views have ultimately played a pivotal role in motivating much recent observational, theoretical, and modeling research aimed at unraveling the workings of multiscale interactions within the tropical atmosphere.

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REFERENCES

- Back, L. E., and C. S. Bretherton, 2009a: On the relationship between SST gradients, boundary layer winds, and convergence

- over the tropical oceans. *J. Climate*, **22**, 4182–4196, doi:[10.1175/2009JCLI2392.1](https://doi.org/10.1175/2009JCLI2392.1).
- , and —, 2009b: A simple model of climatological rainfall and vertical motion patterns over the tropical oceans. *J. Climate*, **22**, 6477–6497, doi:[10.1175/2009JCLI2393.1](https://doi.org/10.1175/2009JCLI2393.1).
- Baldwin, M. P., and Coauthors, 2001: The quasi-biennial oscillation. *Rev. Geophys.*, **39**, 179–229, doi:[10.1029/1999RG000073](https://doi.org/10.1029/1999RG000073).
- Berry, G. J., and C. D. Thorncroft, 2012: African easterly wave dynamics in a mesoscale numerical model: The upscale role of convection. *J. Atmos. Sci.*, **69**, 1267–1283, doi:[10.1175/JAS-D-11-099.1](https://doi.org/10.1175/JAS-D-11-099.1).
- Bretherton, C. S., M. E. Peters, and L. E. Back, 2004: Relationships between water vapor path and precipitation over the tropical oceans. *J. Climate*, **17**, 1517–1528, doi:[10.1175/1520-0442\(2004\)017<1517:RBWVPA>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<1517:RBWVPA>2.0.CO;2).
- Bretherton, F. P., 1964: Low frequency oscillations trapped near the equator. *Tellus*, **16**, 181–185, doi:[10.1111/j.2153-3490.1964.tb00159.x](https://doi.org/10.1111/j.2153-3490.1964.tb00159.x).
- Burpee, R. W., 1972: The origin and structure of easterly waves in the lower troposphere of North Africa. *J. Atmos. Sci.*, **29**, 77–89, doi:[10.1175/1520-0469\(1972\)029<0077:TOASOE>2.0.CO;2](https://doi.org/10.1175/1520-0469(1972)029<0077:TOASOE>2.0.CO;2).
- Chang, C.-P., 1970: Westward propagating cloud patterns in the tropical Pacific as seen from time-composite satellite photographs. *J. Atmos. Sci.*, **27**, 133–138, doi:[10.1175/1520-0469\(1970\)027<0133:WPCPIT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1970)027<0133:WPCPIT>2.0.CO;2).
- Charney, J. G., 1963: A note on large-scale motions in the tropics. *J. Atmos. Sci.*, **20**, 607–609, doi:[10.1175/1520-0469\(1963\)020<0607:ANOLSM>2.0.CO;2](https://doi.org/10.1175/1520-0469(1963)020<0607:ANOLSM>2.0.CO;2).
- , 1969: A further note on large-scale motions in the tropics. *J. Atmos. Sci.*, **26**, 182–185, doi:[10.1175/1520-0469\(1969\)026<0182:AFNOLS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1969)026<0182:AFNOLS>2.0.CO;2).
- , and P. G. Drazin, 1961: Propagation of planetary-scale disturbances from the lower into the upper atmosphere. *J. Geophys. Res.*, **66**, 83–109, doi:[10.1029/JZ066i001p00083](https://doi.org/10.1029/JZ066i001p00083).
- , and M. E. Stern, 1962: On the stability of internal baroclinic jets in a rotating atmosphere. *J. Atmos. Sci.*, **19**, 159–172, doi:[10.1175/1520-0469\(1962\)019<0159:OTSOIB>2.0.CO;2](https://doi.org/10.1175/1520-0469(1962)019<0159:OTSOIB>2.0.CO;2).
- Chen, G., and C.-Y. Tam, 2012: A new perspective on the excitation of low-tropospheric mixed Rossby–gravity waves in association with energy dispersion. *J. Atmos. Sci.*, **69**, 1397–1403, doi:[10.1175/JAS-D-11-0331.1](https://doi.org/10.1175/JAS-D-11-0331.1).
- Cornforth, R. J., B. J. Hoskins, and C. D. Thorncroft, 2009: The impact of moist processes on the African easterly jet and African easterly wave system. *Quart. J. Roy. Meteor. Soc.*, **135**, 894–913, doi:[10.1002/qj.414](https://doi.org/10.1002/qj.414).
- Dunkerton, T. J., 1991: Intensity variation and coherence of 3–6 day equatorial waves. *Geophys. Res. Lett.*, **18**, 1469–1472, doi:[10.1029/91GL01780](https://doi.org/10.1029/91GL01780).
- , 1993: Observation of 3–6-day meridional wind oscillations over the tropical Pacific, 1973–1992: Vertical structure and interannual variability. *J. Atmos. Sci.*, **50**, 3292–3291, doi:[10.1175/1520-0469\(1993\)050<3292:OODMWO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1993)050<3292:OODMWO>2.0.CO;2).
- , 1997: The role of gravity waves in the quasi-biennial oscillation. *J. Geophys. Res.*, **102**, 26 053–26 076, doi:[10.1029/96JD02999](https://doi.org/10.1029/96JD02999).
- , and M. P. Baldwin, 1995: Observation of 3–6-day meridional wind oscillations over the tropical Pacific, 1973–1992: Horizontal structure and propagation. *J. Atmos. Sci.*, **52**, 1585–1601, doi:[10.1175/1520-0469\(1995\)052<1585:OODMWO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<1585:OODMWO>2.0.CO;2).
- , M. T. Montgomery, and Z. Wang, 2009: Tropical cyclogenesis in a tropical wave critical layer: Easterly waves. *Atmos. Chem. Phys.*, **9**, 5587–5646, doi:[10.5194/acp-9-5587-2009](https://doi.org/10.5194/acp-9-5587-2009).
- Ebdon, R. A., 1960: Notes on the wind flow at 50 mb in tropical and sub-tropical regions in January 1957 and January 1958. *Quart. J. Roy. Meteor. Soc.*, **86**, 540–542, doi:[10.1002/qj.49708637011](https://doi.org/10.1002/qj.49708637011).
- Ferreira, R. N., and W. H. Schubert, 1997: Barotropic aspects of ITCZ breakdown. *J. Atmos. Sci.*, **54**, 261–285, doi:[10.1175/1520-0469\(1997\)054<0261:BAOIB>2.0.CO;2](https://doi.org/10.1175/1520-0469(1997)054<0261:BAOIB>2.0.CO;2).
- Fovell, R. G., Y. P. Bu, K. L. Corbosiero, W.-W. Tung, Y. Cao, H.-C. Kuo, L.-H. Hsu, and H. Su, 2016: Influence of cloud microphysics and radiation on tropical cyclone structure and motion. *Multi-scale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai, Meteor. Monogr.*, No. 56, Amer. Meteor. Soc., doi:[10.1175/AMSMONOGRAPHS-D-15-0006.1](https://doi.org/10.1175/AMSMONOGRAPHS-D-15-0006.1).
- Frenkel, Y., A. Majda, and B. Khouider, 2012: Using the stochastic multicloud model to improve tropical convective parameterization: A paradigm example. *J. Atmos. Sci.*, **69**, 1080–1104, doi:[10.1175/JAS-D-11-0148.1](https://doi.org/10.1175/JAS-D-11-0148.1).
- Gamache, J. F., and R. A. Houze, 1985: Further analysis of the composite wind and thermodynamic structure of the 12 September GATE squall line. *Mon. Wea. Rev.*, **113**, 1241–1259, doi:[10.1175/1520-0493\(1985\)113<1241:FAOTCW>2.0.CO;2](https://doi.org/10.1175/1520-0493(1985)113<1241:FAOTCW>2.0.CO;2).
- Hall, N. M. J., G. N. Kiladis, and C. D. Thorncroft, 2006: Three-dimensional structure and dynamics of African easterly waves. Part II: Dynamical modes. *J. Atmos. Sci.*, **63**, 2231–2245, doi:[10.1175/JAS3742.1](https://doi.org/10.1175/JAS3742.1).
- Hayashi, Y., 1971: A generalized method of resolving disturbances into progressive and retrogressive waves by space Fourier and time cross-spectral analyses. *J. Meteor. Soc. Japan*, **49**, 125–128.
- Hendon, H.-H., and B. Liebmann, 1991: The structure and annual variation of antisymmetric fluctuations of tropical convection and their association with Rossby–gravity waves. *J. Atmos. Sci.*, **48**, 2127–2140, doi:[10.1175/1520-0469\(1991\)048<2127:TSAAVO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1991)048<2127:TSAAVO>2.0.CO;2).
- Hohenegger, C., and B. Stevens, 2013: Preconditioning deep convection with cumulus congestus. *J. Atmos. Sci.*, **70**, 448–464, doi:[10.1175/JAS-D-12-089.1](https://doi.org/10.1175/JAS-D-12-089.1).
- Holton, J. R., 1970: A note on forced equatorial waves. *Mon. Wea. Rev.*, **98**, 614–615, doi:[10.1175/1520-0493\(1970\)098<0614:ANOFEW>2.3.CO;2](https://doi.org/10.1175/1520-0493(1970)098<0614:ANOFEW>2.3.CO;2).
- , and R. S. Lindzen, 1972: An updated theory for the quasi-biennial cycle of the tropical stratosphere. *J. Atmos. Sci.*, **29**, 1076–1080, doi:[10.1175/1520-0469\(1972\)029<1076:AUTFTQ>2.0.CO;2](https://doi.org/10.1175/1520-0469(1972)029<1076:AUTFTQ>2.0.CO;2).
- Horinouchi, T., F. Sassi, and B. A. Boville, 2000: Synoptic-scale Rossby waves and the geographic distribution of lateral transport routes between the tropics and the extratropics in the lower stratosphere. *J. Geophys. Res.*, **105**, 26 579–26 592, doi:[10.1029/2000JD900281](https://doi.org/10.1029/2000JD900281).
- Hoskins, B. J., and G. Y. Yang, 2000: The equatorial response to higher latitude forcing. *J. Atmos. Sci.*, **57**, 1197–1213, doi:[10.1175/1520-0469\(2000\)057<1197:TERTHL>2.0.CO;2](https://doi.org/10.1175/1520-0469(2000)057<1197:TERTHL>2.0.CO;2).
- Houze, R. A., Jr., and A. K. Betts, 1981: Convection in GATE. *Rev. Geophys.*, **19**, 541–576, doi:[10.1029/RG019i004p00541](https://doi.org/10.1029/RG019i004p00541).
- Hsieh, J.-S., and K. H. Cook, 2008: On the instability of the African easterly jet and the generation of African waves: Reversals of the potential vorticity gradient. *J. Atmos. Sci.*, **65**, 2130–2151, doi:[10.1175/2007JAS2552.1](https://doi.org/10.1175/2007JAS2552.1).
- Itoh, H., and M. Ghil, 1988: The generation mechanism of mixed Rossby–gravity waves in the equatorial troposphere. *J. Atmos. Sci.*, **45**, 585–604, doi:[10.1175/1520-0469\(1988\)045<0585:TGMOMR>2.0.CO;2](https://doi.org/10.1175/1520-0469(1988)045<0585:TGMOMR>2.0.CO;2).
- Johnson, R. H., T. Rickenbach, S. A. Rutledge, P. Ciesielski, and W. Schubert, 1999: Trimodal characteristics of tropical convection. *J. Climate*, **12**, 2397–2418, doi:[10.1175/1520-0442\(1999\)012<2397:TCOTC>2.0.CO;2](https://doi.org/10.1175/1520-0442(1999)012<2397:TCOTC>2.0.CO;2).
- Kawatani, Y., M. Takahashi, K. Sato, S. P. Alexander, and T. Tsuda, 2009: Global distribution of atmospheric waves in the equatorial upper troposphere and lower stratosphere:

- AGCM simulation of sources and propagation. *J. Geophys. Res.*, **114**, D01102, doi:[10.1029/2008JD010374](https://doi.org/10.1029/2008JD010374).
- Khouider, B., and A. Majda, 2006: A simple multicloud parameterization for convectively coupled tropical waves. Part I: Linear analysis. *J. Atmos. Sci.*, **63**, 1308–1323, doi:[10.1175/JAS3677.1](https://doi.org/10.1175/JAS3677.1).
- Kiladis, G. N., 1998: Observations of Rossby waves linked to convection over the eastern tropical Pacific. *J. Atmos. Sci.*, **55**, 321–339, doi:[10.1175/1520-0469\(1998\)055<0321:OORWLT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1998)055<0321:OORWLT>2.0.CO;2).
- , and K. M. Weickmann, 1992: Extratropical forcing of tropical Pacific convection during northern winter. *Mon. Wea. Rev.*, **120**, 1924–1939, doi:[10.1175/1520-0493\(1992\)120<1924:EFOTPC>2.0.CO;2](https://doi.org/10.1175/1520-0493(1992)120<1924:EFOTPC>2.0.CO;2).
- , and M. Wheeler, 1995: Horizontal and vertical structure of observed tropospheric equatorial Rossby waves. *J. Geophys. Res.*, **100**, 22 981–22 997, doi:[10.1029/95JD02415](https://doi.org/10.1029/95JD02415).
- , K. H. Straub, and P. T. Haertel, 2005: Zonal and vertical structure of the Madden–Julian oscillation. *J. Atmos. Sci.*, **62**, 2790–2809, doi:[10.1175/JAS3520.1](https://doi.org/10.1175/JAS3520.1).
- , C. D. Thorncroft, and N. M. J. Hall, 2006: Three-dimensional structure and dynamics of African easterly waves. Part I: Observations. *J. Atmos. Sci.*, **63**, 2212–2230, doi:[10.1175/JAS3741.1](https://doi.org/10.1175/JAS3741.1).
- , M. C. Wheeler, P. T. Haertel, K. H. Straub, and P. E. Roundy, 2009: Convectively coupled equatorial waves. *Rev. Geophys.*, **47**, RG2003, doi:[10.1029/2008RG000266](https://doi.org/10.1029/2008RG000266).
- Knippertz, P., 2007: Tropical–extratropical interactions related to upper-level troughs at low latitudes. *Dyn. Atmos. Oceans*, **43**, 36–62, doi:[10.1016/j.dynatmoce.2006.06.003](https://doi.org/10.1016/j.dynatmoce.2006.06.003).
- Krishnamurti, T. N., 1971: Observational study of the tropical upper tropospheric motion field during the Northern Hemisphere summer. *J. Appl. Meteor.*, **10**, 1066–1096, doi:[10.1175/1520-0450\(1971\)010<1066:OSOTTU>2.0.CO;2](https://doi.org/10.1175/1520-0450(1971)010<1066:OSOTTU>2.0.CO;2).
- , R. Krishnamurti, A. Simon, A. Thomas, and V. Kumar, 2016: A mechanism of the MJO invoking scale interactions. *Multiscale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai*, Meteor. Monogr., No. 56, Amer. Meteor. Soc., doi:[10.1175/AMSMONOGRAPH5-D-15-0009.1](https://doi.org/10.1175/AMSMONOGRAPH5-D-15-0009.1).
- Kubar, T. L., D. A. Hartman, and R. Wood, 2007: Radiative and convective driving of tropical high clouds. *J. Climate*, **20**, 5510–5526, doi:[10.1175/2007JCLI1628.1](https://doi.org/10.1175/2007JCLI1628.1).
- Liebmann, B., and H.-H. Hendon, 1990: Synoptic-scale disturbances near the equator. *J. Atmos. Sci.*, **47**, 1463–1479, doi:[10.1175/1520-0469\(1990\)047<1463:SSDNTE>2.0.CO;2](https://doi.org/10.1175/1520-0469(1990)047<1463:SSDNTE>2.0.CO;2).
- , G. N. Kiladis, L. M. V. Carvalho, C. Jones, C. S. Vera, I. Bladé, and D. Allured, 2009: Origin of convectively coupled Kelvin waves over South America. *J. Climate*, **22**, 300–315, doi:[10.1175/2008JCLI2340.1](https://doi.org/10.1175/2008JCLI2340.1).
- Lin, X., and R. H. Johnson, 1996: Kinematic and thermodynamic characteristics of the flow over the western Pacific warm pool during TOGA COARE. *J. Atmos. Sci.*, **53**, 695–715, doi:[10.1175/1520-0469\(1996\)053<0695:KATCOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1996)053<0695:KATCOT>2.0.CO;2).
- Lindzen, R. S., 1967: Planetary waves on beta planes. *Mon. Wea. Rev.*, **95**, 441–451, doi:[10.1175/1520-0493\(1967\)095<0441:PWOBP>2.3.CO;2](https://doi.org/10.1175/1520-0493(1967)095<0441:PWOBP>2.3.CO;2).
- , 1974: Wave-CISK and tropical spectra. *J. Atmos. Sci.*, **31**, 1447–1449, doi:[10.1175/1520-0469\(1974\)031<1447:WCATS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1974)031<1447:WCATS>2.0.CO;2).
- , and J. R. Holton, 1968: A theory of the quasi-biennial oscillation. *J. Atmos. Sci.*, **25**, 1095–1107, doi:[10.1175/1520-0469\(1968\)025<1095:ATOTQB>2.0.CO;2](https://doi.org/10.1175/1520-0469(1968)025<1095:ATOTQB>2.0.CO;2).
- , and T. Matsuno, 1968: On the nature of large scale wave disturbances in the equatorial lower stratosphere. *J. Meteor. Soc. Japan*, **46**, 215–220.
- Longuet-Higgins, M. S., 1968: The eigenfunctions of Laplace’s tidal equations over a sphere. *Philos. Trans. Roy. Soc. London*, **A262**, 511–607. [Available online at <http://www.jstor.org/stable/73582>.]
- Magaña, V., and M. Yanai, 1991: Tropical–midlatitude interaction on the time scale of 30 to 60 days during the northern summer of 1979. *J. Climate*, **4**, 180–201, doi:[10.1175/1520-0442\(1991\)004<0180:TMIOTT>2.0.CO;2](https://doi.org/10.1175/1520-0442(1991)004<0180:TMIOTT>2.0.CO;2).
- , and —, 1995: Mixed Rossby–gravity waves triggered by lateral forcing. *J. Atmos. Sci.*, **52**, 1473–1486, doi:[10.1175/1520-0469\(1995\)052<1473:MRWTBL>2.0.CO;2](https://doi.org/10.1175/1520-0469(1995)052<1473:MRWTBL>2.0.CO;2).
- Majda, A., and B. Khouider, 2002: Stochastic and mesoscopic models for tropical convection. *Proc. Natl. Acad. Sci. USA*, **99**, 1123–1128, doi:[10.1073/pnas.032663199](https://doi.org/10.1073/pnas.032663199).
- Mak, M.-K., 1969: Laterally driven stochastic motions in the tropics. *J. Atmos. Sci.*, **26**, 41–64, doi:[10.1175/1520-0469\(1969\)026<0041:LDSMIT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1969)026<0041:LDSMIT>2.0.CO;2).
- Maloney, E. D., and C. Zhang, 2016: Dr. Yanai’s contributions to the discovery and science of the MJO. *Multiscale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai*, Meteor. Monogr., No. 56, Amer. Meteor. Soc., doi:[10.1175/AMSMONOGRAPH5-D-15-0003.1](https://doi.org/10.1175/AMSMONOGRAPH5-D-15-0003.1).
- Mapes, B., S. Tulich, J.-L. Lin, and P. Zuidema, 2006: The mesoscale convection life cycle: Building block or prototype for large-scale tropical waves? *Dyn. Atmos. Oceans*, **42**, 3–29, doi:[10.1016/j.dynatmoce.2006.03.003](https://doi.org/10.1016/j.dynatmoce.2006.03.003).
- Maruyama, T., 1967: Large-scale disturbances in the equatorial lower stratosphere. *J. Meteor. Soc. Japan*, **45**, 391–408.
- , 1968: Time sequence of power spectra of disturbances in the equatorial lower stratosphere in relation to the quasi-biennial oscillation. *J. Meteor. Soc. Japan*, **46**, 327–341.
- , and M. Yanai, 1967: Evidence of large-scale wave disturbances in the equatorial lower stratosphere. *J. Meteor. Soc. Japan*, **45**, 196–199.
- Matsuno, T., 1966: Quasi-geostrophic motions in the equatorial area. *J. Meteor. Soc. Japan*, **44**, 25–43.
- Montgomery, M. T., and Coauthors, 2012: The Pre-Depression Investigation of Cloud-Systems in the Tropics (PREDICT) experiment: Scientific basis, new analysis tools, and some first results. *Bull. Amer. Meteor. Sci.*, **93**, 153–172, doi:[10.1175/BAMS-D-11-00046.1](https://doi.org/10.1175/BAMS-D-11-00046.1).
- Murakami, T., and F. P. Ho, 1972a: Spectrum analysis of cloudiness over the northern Pacific. *J. Meteor. Soc. Japan*, **50**, 285–300.
- , and —, 1972b: Spectrum analysis of cloudiness over the Pacific. *J. Meteor. Soc. Japan*, **50**, 301–311.
- Nakazawa, T., 1988: Tropical super clusters within intraseasonal variations over the western Pacific. *J. Meteor. Soc. Japan*, **66**, 823–839.
- Neelin, J. D., and I. M. Held, 1987: Modeling tropical convergence based on the moist static energy budget. *Mon. Wea. Rev.*, **115**, 3–12, doi:[10.1175/1520-0493\(1987\)115<0003:MTCBOT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115<0003:MTCBOT>2.0.CO;2).
- Neggers, R. A. J., J. D. Neelin, and B. Stevens, 2007: Impact mechanisms of shallow cumulus convection on tropical climate dynamics. *J. Climate*, **20**, 2623–2642, doi:[10.1175/JCLI4079.1](https://doi.org/10.1175/JCLI4079.1).
- Nesbitt, S. W., R. Cifelli, and S. A. Rutledge, 2006: Storm morphology and rainfall characteristics of TRMM precipitation features. *Mon. Wea. Rev.*, **134**, 2702–2721, doi:[10.1175/MWR3200.1](https://doi.org/10.1175/MWR3200.1).
- Nitta, T., 1970a: Statistical study of tropospheric wave disturbances in the tropical Pacific region. *J. Meteor. Soc. Japan*, **48**, 47–60.
- , 1970b: A study of generation and conversion of eddy available potential energy in the tropics. *J. Meteor. Soc. Japan*, **48**, 524–528.
- , 1972: Energy budget of wave disturbances over the Marshall Islands during the years of 1956 and 1958. *J. Meteor. Soc. Japan*, **50**, 71–84.

- , 1977: Response of cumulus updraft and downdraft to GATE A/B-scale motion systems. *J. Atmos. Sci.*, **34**, 1163–1186, doi:[10.1175/1520-0469\(1977\)034<1163:ROCUAD>2.0.CO;2](https://doi.org/10.1175/1520-0469(1977)034<1163:ROCUAD>2.0.CO;2).
- , 1978: A diagnostic study of interaction of cumulus updrafts and downdrafts with large-scale motions in GATE. *J. Meteor. Soc. Japan*, **56**, 232–242.
- , and M. Yanai, 1969: A note on the barotropic instability of the tropical easterly current. *J. Meteor. Soc. Japan*, **47**, 127–130.
- Norquist, D. C., E. E. Recker, and R. J. Reed, 1977: The energetics of African wave disturbances as observed during Phase III of GATE. *Mon. Wea. Rev.*, **105**, 334–342, doi:[10.1175/1520-0493\(1977\)105<0334:TEOAWD>2.0.CO;2](https://doi.org/10.1175/1520-0493(1977)105<0334:TEOAWD>2.0.CO;2).
- Palmer, C. E., 1951: Tropical meteorology. *Compendium of Meteorology*, Amer. Meteor. Soc., 859–880.
- , 1952: Tropical meteorology. *Quart. J. Roy. Meteor. Soc.*, **78**, 126–163, doi:[10.1002/qj.49707833603](https://doi.org/10.1002/qj.49707833603).
- Priestley, C. H. B., 1959: *Turbulent Transfer in the Lower Atmosphere*. University of Chicago Press, 130 pp.
- Randel, W. J., 1992: Upper tropospheric equatorial waves in ECMWF analyses. *Quart. J. Roy. Meteor. Soc.*, **118**, 365–394, doi:[10.1002/qj.49711850409](https://doi.org/10.1002/qj.49711850409).
- Raymond, D. J., S. L. Sessions, A. H. Sobel, and Z. Fuchs, 2009: The mechanics of gross moist stability. *J. Adv. Model. Earth Syst.*, **1** (9), doi:[10.3894/JAMES.2009.1.9](https://doi.org/10.3894/JAMES.2009.1.9).
- Reed, R. J., 1962: Evidence of geostrophic motion in the equatorial stratosphere. *Quart. J. Roy. Meteor. Soc.*, **88**, 324–327, doi:[10.1002/qj.49708837711](https://doi.org/10.1002/qj.49708837711).
- , and E. E. Recker, 1971: Structure and properties of synoptic-scale wave disturbances in the equatorial western Pacific. *J. Atmos. Sci.*, **28**, 1117–1133, doi:[10.1175/1520-0469\(1971\)028<1117:SAPOSS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1971)028<1117:SAPOSS>2.0.CO;2).
- , W. J. Campbell, L. A. Rasmussen, and D. G. Rogers, 1961: Evidence of downward-propagating annual wind reversal in the equatorial stratosphere. *J. Geophys. Res.*, **66**, 813–818, doi:[10.1029/JZ066i003p00813](https://doi.org/10.1029/JZ066i003p00813).
- , D. C. Norquist, and E. E. Recker, 1977: The structure and properties of African wave disturbances as observed during Phase III of GATE. *Mon. Wea. Rev.*, **105**, 317–333, doi:[10.1175/1520-0493\(1977\)105<0317:TSAPOA>2.0.CO;2](https://doi.org/10.1175/1520-0493(1977)105<0317:TSAPOA>2.0.CO;2).
- Riehl, H., 1945: Waves in the easterlies and the polar front in the tropics. Department of Meteorology, University of Chicago Misc. Rep. 17, 79 pp.
- , 1948: On the formation of typhoons. *J. Meteor.*, **5**, 247–265, doi:[10.1175/1520-0469\(1948\)005<0247:OTFOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1948)005<0247:OTFOT>2.0.CO;2).
- Rosenthal, S. L., 1960: Some estimates of the power spectra of large-scale disturbances in low latitudes. *J. Meteor.*, **17**, 259–263, doi:[10.1175/1520-0469\(1960\)017<0259:SEOTPS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1960)017<0259:SEOTPS>2.0.CO;2).
- , 1965: Some preliminary theoretical considerations of tropospheric wave motions in equatorial latitudes. *Mon. Wea. Rev.*, **93**, 605–612, doi:[10.1175/1520-0493\(1965\)093<0605:SPTCOT>2.3.CO;2](https://doi.org/10.1175/1520-0493(1965)093<0605:SPTCOT>2.3.CO;2).
- Roundy, P. E., and W. M. Frank, 2004: A climatology of waves in the equatorial region. *J. Atmos. Sci.*, **61**, 2105–2132, doi:[10.1175/1520-0469\(2004\)061<2105:ACOWIT>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<2105:ACOWIT>2.0.CO;2).
- Serra, Y. L., and R. A. Houze, 2002: Observations of variability on synoptic timescales in the east Pacific ITCZ. *J. Atmos. Sci.*, **59**, 1723–1743, doi:[10.1175/1520-0469\(2002\)059<1723:OOVOST>2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059<1723:OOVOST>2.0.CO;2).
- , G. N. Kiladis, and M. F. Cronin, 2008: Horizontal and vertical structure of easterly waves in the Pacific ITCZ. *J. Atmos. Sci.*, **65**, 1266–1284, doi:[10.1175/2007JAS2341.1](https://doi.org/10.1175/2007JAS2341.1).
- , —, and K. L. Hodges, 2010: Tracking and mean structure of easterly waves over the Intra-America Sea. *J. Climate*, **23**, 4823–4840, doi:[10.1175/2010JCLI3223.1](https://doi.org/10.1175/2010JCLI3223.1).
- Sherwood, S. C., 1999: Convective precursors and predictability in the tropical western Pacific. *Mon. Wea. Rev.*, **127**, 2977–2991, doi:[10.1175/1520-0493\(1999\)127<2977:CPAPIT>2.0.CO;2](https://doi.org/10.1175/1520-0493(1999)127<2977:CPAPIT>2.0.CO;2).
- Sikdar, D. N., and V. E. Suomi, 1971: Time variation of tropical energetics as viewed from a geostationary satellite. *J. Atmos. Sci.*, **28**, 170–180, doi:[10.1175/1520-0469\(1971\)028<0170:TVOTEAS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1971)028<0170:TVOTEAS>2.0.CO;2).
- Straub, K. H., and G. N. Kiladis, 2003: Interaction between the boreal summer intraseasonal oscillation and higher-frequency tropical wave activity. *Mon. Wea. Rev.*, **131**, 945–960, doi:[10.1175/1520-0493\(2003\)131<0945:IBTBSI>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<0945:IBTBSI>2.0.CO;2).
- Tai, K.-S., and Y. Ogura, 1987: An observational study of easterly waves over the eastern Pacific in the northern summer using FGGE data. *J. Atmos. Sci.*, **44**, 339–361, doi:[10.1175/1520-0469\(1987\)044<0339:AOSOEWS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1987)044<0339:AOSOEWS>2.0.CO;2).
- Takayabu, Y. N., 1994a: Large-scale cloud disturbances associated with equatorial waves. Part I: Spectral features of the cloud disturbances. *J. Meteor. Soc. Japan*, **72**, 433–449.
- , 1994b: Large-scale cloud disturbances associated with equatorial waves. Part II: Westward-propagating inertio-gravity waves. *J. Meteor. Soc. Japan*, **72**, 451–465.
- , and M. Murakami, 1991: The composite structure of super cloud clusters observed over the Pacific Ocean in June 1–20, 1986 and their relationship with easterly waves. *J. Meteor. Soc. Japan*, **69**, 105–125.
- , and T. Nitta, 1993: 3–5 day-period disturbances coupled with convection over the tropical Pacific Ocean. *J. Meteor. Soc. Japan*, **71**, 221–246.
- , K.-M. Lau, and C.-H. Sui, 1996: Observation of a quasi-2-day wave during TOGA COARE. *Mon. Wea. Rev.*, **124**, 1892–1913, doi:[10.1175/1520-0493\(1996\)124<1892:OOAQDW>2.0.CO;2](https://doi.org/10.1175/1520-0493(1996)124<1892:OOAQDW>2.0.CO;2).
- , T. Iguchi, M. Kachi, A. Shibata, and H. Kanzawa, 1999: Abrupt termination of the 1997–98 El Niño in response to a Madden–Julian oscillation. *Nature*, **402**, 279–282, doi:[10.1038/46254](https://doi.org/10.1038/46254).
- , S. Shige, W.-K. Tao, and N. Hirota, 2010: Shallow and deep latent heating modes over tropical oceans observed with TRMM PR spectral latent heating data. *J. Climate*, **23**, 2030–2046, doi:[10.1175/2009JCLI3110.1](https://doi.org/10.1175/2009JCLI3110.1).
- Takemi, T., O. Hirayama, and C. Liu, 2004: Factors responsible for the vertical development of tropical oceanic cumulus convection. *Geophys. Res. Lett.*, **31**, L11109, doi:[10.1029/2004GL020225](https://doi.org/10.1029/2004GL020225).
- Tanaka, H., and O. Ryuguji, 1971: Spectrum analysis of tropical cloudiness (I). *J. Meteor. Soc. Japan*, **49**, 13–19.
- , and —, 1973: Spectrum analysis of tropical cloudiness (II). *J. Meteor. Soc. Japan*, **51**, 93–100.
- Tao, W.-K., and Coauthors, 2016: TRMM latent heating retrieval: Applications and comparisons with field campaigns and large-scale analyses. *Multiscale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai*, Meteor. Monogr., No. 56, Amer. Meteor. Soc., doi:[10.1175/AMSMONOGRAPHS-D-15-0013.1](https://doi.org/10.1175/AMSMONOGRAPHS-D-15-0013.1).
- Thompson, R. M., S. W. Payne, E. E. Recker, and R. J. Reed, 1979: Structure and properties of synoptic-scale wave disturbances in the intertropical convergence zone of the eastern Atlantic. *J. Atmos. Sci.*, **36**, 53–72, doi:[10.1175/1520-0469\(1979\)036<0053:SAPOSS>2.0.CO;2](https://doi.org/10.1175/1520-0469(1979)036<0053:SAPOSS>2.0.CO;2).
- Thorncroft, C. D., N. M. J. Hall, and G. N. Kiladis, 2008: Three-dimensional structure and dynamics of African easterly waves. Part III: Genesis. *J. Atmos. Sci.*, **65**, 3596–3607, doi:[10.1175/2008JAS2575.1](https://doi.org/10.1175/2008JAS2575.1).
- Toma, V. E., and P. J. Webster, 2010: Oscillations of the inter-tropical convergence zone and the genesis of easterly waves.

- Part I: Diagnostics and theory. *Climate Dyn.*, **34**, 587–604, doi:[10.1007/s00382-009-0584-x](https://doi.org/10.1007/s00382-009-0584-x).
- Tomas, R. A., and P. J. Webster, 1994: Horizontal and vertical structure of cross-equatorial wave propagation. *J. Atmos. Sci.*, **51**, 1417–1430, doi:[10.1175/1520-0469\(1994\)051<1417:HAVSOC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1994)051<1417:HAVSOC>2.0.CO;2).
- , and —, 1997: The role of inertial instability in determining the location and strength of near-equatorial convection. *Quart. J. Roy. Meteor. Soc.*, **123**, 1445–1482, doi:[10.1002/qj.49712354202](https://doi.org/10.1002/qj.49712354202).
- Tucker, G. B., 1968: The 26-month zonal wind oscillation in the lower stratosphere of the Southern Hemisphere. *J. Atmos. Sci.*, **25**, 293–298, doi:[10.1175/1520-0469\(1968\)025<0293:TMZWOI>2.0.CO;2](https://doi.org/10.1175/1520-0469(1968)025<0293:TMZWOI>2.0.CO;2).
- Wallace, J. M., 1971: Spectral studies of tropospheric wave disturbances in the tropical western Pacific. *Rev. Geophys.*, **9**, 557–612, doi:[10.1029/RG009i003p00557](https://doi.org/10.1029/RG009i003p00557).
- , and V. E. Kousky, 1968: Observational evidence of Kelvin waves in the tropical stratosphere. *J. Atmos. Sci.*, **25**, 900–907, doi:[10.1175/1520-0469\(1968\)025<0900:OEOKWI>2.0.CO;2](https://doi.org/10.1175/1520-0469(1968)025<0900:OEOKWI>2.0.CO;2).
- , and C.-P. Chang, 1969: Spectrum analysis of large-scale wave disturbances in the tropical lower troposphere. *J. Atmos. Sci.*, **26**, 1010–1025, doi:[10.1175/1520-0469\(1969\)026<1010:SAOLSW>2.0.CO;2](https://doi.org/10.1175/1520-0469(1969)026<1010:SAOLSW>2.0.CO;2).
- , and L. A. Chang, 1972: On the application of satellite data on cloud brightness to the study of tropical wave disturbances. *J. Atmos. Sci.*, **29**, 1400–1403, doi:[10.1175/1520-0469\(1972\)029<1400:OTAOSD>2.0.CO;2](https://doi.org/10.1175/1520-0469(1972)029<1400:OTAOSD>2.0.CO;2).
- Wang, C.-C., and G. Magnusdottir, 2005: ITCZ breakdowns in three-dimensional flows. *J. Atmos. Sci.*, **62**, 1497–1512, doi:[10.1175/JAS3409.1](https://doi.org/10.1175/JAS3409.1).
- Wang, Z., M. T. Montgomery, and T. J. Dunkerton, 2010: Genesis of pre-hurricane Felix (2007). Part I: The role of the easterly wave critical layer. *J. Atmos. Sci.*, **67**, 1711–1729, doi:[10.1175/2009JAS3420.1](https://doi.org/10.1175/2009JAS3420.1).
- Webster, P. J., and J. R. Holton, 1982: Cross-equatorial response to middle-latitude forcing in a zonally varying basic state. *J. Atmos. Sci.*, **39**, 722–733, doi:[10.1175/1520-0469\(1982\)039<0722:CERTML>2.0.CO;2](https://doi.org/10.1175/1520-0469(1982)039<0722:CERTML>2.0.CO;2).
- , and H.-R. Chang, 1988: Equatorial energy accumulation and emanation regions: Impacts of a zonally varying basic state. *J. Atmos. Sci.*, **45**, 803–829, doi:[10.1175/1520-0469\(1988\)045<0803:EEAAER>2.0.CO;2](https://doi.org/10.1175/1520-0469(1988)045<0803:EEAAER>2.0.CO;2).
- Wheeler, M., and G. N. Kiladis, 1999: Convectively coupled equatorial waves: Analysis of clouds and temperature in the wavenumber–frequency domain. *J. Atmos. Sci.*, **56**, 374–399, doi:[10.1175/1520-0469\(1999\)056<0374:CCEWAO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1999)056<0374:CCEWAO>2.0.CO;2).
- Wu, Z., 2003: A shallow CISK, deep equilibrium mechanisms for the interaction between large-scale convection and large-scale circulations in the tropics. *J. Atmos. Sci.*, **60**, 377–392, doi:[10.1175/1520-0469\(2003\)060<0377:ASCDem>2.0.CO;2](https://doi.org/10.1175/1520-0469(2003)060<0377:ASCDem>2.0.CO;2).
- Yamasaki, M., 1969: Large-scale disturbances in a conditionally unstable atmosphere in low latitudes. *Pap. Meteor. Geophys.*, **20**, 289–336, doi:[10.2467/mripapers1950.20.4_289](https://doi.org/10.2467/mripapers1950.20.4_289).
- Yanai, M., 1961a: A detailed analysis of typhoon formation. *J. Meteor. Soc. Japan*, **39**, 187–214.
- , 1961b: Dynamical aspects of typhoon formation. *J. Meteor. Soc. Japan*, **39**, 282–309.
- , 1963: A comment on the creation of warm core in incipient tropical cyclone. *J. Meteor. Soc. Japan*, **41**, 183–187.
- , 1964: Formation of tropical cyclones. *Rev. Geophys.*, **2**, 367–414, doi:[10.1029/RG002i002p00367](https://doi.org/10.1029/RG002i002p00367).
- , 1971a: A review of recent studies of tropical meteorology relevant to the planning of GATE. Experimental Design Proposed by the Interim Scientific and Management Group (ISMG), Vol. 2, Annex I, World Meteorological Organization, 1–43.
- , 1971b: The mass, heat and moisture budgets and the convective heating within tropical cloud clusters. Preprints, *Seventh Tech. Conf. on Hurricanes and Tropical Meteorology*, St. Michael, Barbados, Amer. Meteor. Soc.
- , and T. Maruyama, 1966: Stratospheric wave disturbances propagating over the equatorial Pacific. *J. Meteor. Soc. Japan*, **44**, 291–294.
- , and T. Nitta, 1968: Finite difference approximation for the barotropic instability problem. *J. Meteor. Soc. Japan*, **46**, 389–403.
- , and Y. Hayashi, 1969: Large-scale equatorial waves penetrating from the upper troposphere into the lower stratosphere. *J. Meteor. Soc. Japan*, **47**, 167–182.
- , and M. Murakami, 1970a: A further study of tropical wave disturbances by the use of spectrum analysis. *J. Meteor. Soc. Japan*, **48**, 185–197.
- , and —, 1970b: Spectrum analysis of symmetric and anti-symmetric equatorial waves. *J. Meteor. Soc. Japan*, **48**, 331–347.
- , and M.-M. Lu, 1983: Equatorially trapped waves at the 200 mb level and their association with meridional convergence of wave energy flux. *J. Atmos. Sci.*, **40**, 2785–2803, doi:[10.1175/1520-0469\(1983\)040<2785:ETWATM>2.0.CO;2](https://doi.org/10.1175/1520-0469(1983)040<2785:ETWATM>2.0.CO;2).
- , and R. H. Johnson, 1993: Impacts of cumulus convection on thermodynamic fields. *The Representation of Cumulus Convection in Numerical Models*, Meteor. Monogr., No. 46, Amer. Meteor. Soc., 39–62.
- , T. Maruyama, T. Nitta, and Y. Hayashi, 1968: Power spectra of large-scale disturbances over the tropical Pacific. *J. Meteor. Soc. Japan*, **46**, 308–323.
- , S. Esbensen, and J. Chu, 1973: Determination of average bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611–627, doi:[10.1175/1520-0469\(1973\)030<0611:DOBPOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1973)030<0611:DOBPOT>2.0.CO;2).
- , C.-H. Chu, T. E. Stark, and T. Nitta, 1976: Response of deep and shallow tropical maritime cumuli to large-scale processes. *J. Atmos. Sci.*, **33**, 976–991, doi:[10.1175/1520-0469\(1976\)033<0976:RODAST>2.0.CO;2](https://doi.org/10.1175/1520-0469(1976)033<0976:RODAST>2.0.CO;2).
- Yang, G.-Y., B. Hoskins, and J. Slingo, 2007: Convectively coupled equatorial waves. Part II: Propagation characteristics. *J. Atmos. Sci.*, **64**, 3424–3437, doi:[10.1175/JAS4018.1](https://doi.org/10.1175/JAS4018.1).
- Yokoyama, C., and Y. N. Takayabu, 2012a: Relationships between rain characteristics and environment. Part I: TRMM precipitation feature and the large-scale environment over the tropical Pacific. *Mon. Wea. Rev.*, **140**, 2831–2840, doi:[10.1175/MWR-D-11-00252.1](https://doi.org/10.1175/MWR-D-11-00252.1).
- , and —, 2012b: Relationships between rain characteristics and environment. Part II: Atmospheric disturbances associated with shallow convection over the eastern tropical Pacific. *Mon. Wea. Rev.*, **140**, 2841–2859, doi:[10.1175/MWR-D-11-00251.1](https://doi.org/10.1175/MWR-D-11-00251.1).
- Yoneyama, K., C. Zhang, and C. N. Long, 2013: Tracking pulses of the Madden–Julian oscillation. *Bull. Amer. Meteor. Soc.*, **94**, 1871–1891, doi:[10.1175/BAMS-D-12-00157.1](https://doi.org/10.1175/BAMS-D-12-00157.1).
- Yoshida, K., 1959: A theory of the Cromwell Current (the equatorial undercurrent) and of the equatorial upwelling—An interpretation in a similarity to a coastal circulation. *J. Oceanogr. Soc. Japan*, **15**, 159–170.
- Zangvil, A., and M. Yanai, 1980: Upper tropospheric waves in the tropics. Part I: Dynamical analysis in the wavenumber–frequency domain. *J. Atmos. Sci.*, **37**, 283–298, doi:[10.1175/1520-0469\(1980\)037<0283:UTWITT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1980)037<0283:UTWITT>2.0.CO;2).
- , and —, 1981: Upper tropospheric waves in the tropics. Part II: Association with clouds in the wavenumber–frequency

- domain. *J. Atmos. Sci.*, **38**, 939–953, doi:[10.1175/1520-0469\(1981\)038<0939:UTWITT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1981)038<0939:UTWITT>2.0.CO;2).
- Zhang, C., and P. J. Webster, 1992: Laterally forced equatorial perturbations in a linear model. Part I: Stationary transient flow. *J. Atmos. Sci.*, **49**, 585–607, doi:[10.1175/1520-0469\(1992\)049<0585:LFEPIA>2.0.CO;2](https://doi.org/10.1175/1520-0469(1992)049<0585:LFEPIA>2.0.CO;2).
- , M. McGauley, and N. A. Bond, 2004: Shallow meridional circulation in the tropical eastern Pacific. *J. Climate*, **17**, 133–139, doi:[10.1175/1520-0442\(2004\)017<0133:SMCITT>2.0.CO;2](https://doi.org/10.1175/1520-0442(2004)017<0133:SMCITT>2.0.CO;2).
- , J. Gottschalck, E. D. Maloney, M. W. Moncrieff, F. Vitart, D. E. Waliser, B. Wang, and M. C. Wheeler, 2013: Cracking the MJO nut. *Geophys. Res. Lett.*, **40**, 1223–1230, doi:[10.1002/grl.50244](https://doi.org/10.1002/grl.50244).
- Zhang, G., and X. Song, 2016: Parameterization of microphysical processes in convective clouds in global climate models. *Multiscale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai*, Meteor. Monogr., No. 56, Amer. Meteor. Soc., doi:[10.1175/AMSMONOGRAPHS-D-15-0015.1](https://doi.org/10.1175/AMSMONOGRAPHS-D-15-0015.1).
- Zipser, E. J., 1969: The role of organized unsaturated convective downdrafts in the structure and rapid decay of an equatorial disturbance. *J. Appl. Meteor.*, **8**, 799–814, doi:[10.1175/1520-0450\(1969\)008<0799:TROOUC>2.0.CO;2](https://doi.org/10.1175/1520-0450(1969)008<0799:TROOUC>2.0.CO;2).
- , 1977: Mesoscale and convective-scale downdrafts as distinct components of squall-line circulation. *Mon. Wea. Rev.*, **105**, 1568–1589, doi:[10.1175/1520-0493\(1977\)105<1568:MACDAD>2.0.CO;2](https://doi.org/10.1175/1520-0493(1977)105<1568:MACDAD>2.0.CO;2).