Chapter 4

Dr. Yanai’s Contributions to the Discovery and Science of the MJO

ERIC D. MALONEY
Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

CHIDONG ZHANG
Rosenstiel School of Atmospheric and Marine Science, University of Miami, Miami, Florida

ABSTRACT

This chapter reviews Professor Michio Yanai’s contributions to the discovery and science of the Madden–Julian oscillation (MJO). Professor Yanai’s work on equatorial waves played an inspirational role in the MJO discovery by Roland Madden and Paul Julian. Professor Yanai also made direct and important contributions to MJO research. These research contributions include work on the vertically integrated moist static energy budget, cumulus momentum transport, eddy available potential energy and eddy kinetic energy budgets, and tropical–extratropical interactions. Finally, Professor Yanai left a legacy through his students, who continue to push the bounds of MJO research.

1. Introduction

Among his many achievements in atmospheric science, Professor Yanai made substantial contributions, both directly and indirectly, to the study of the Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972). These contributions are reviewed in this chapter. We first discuss how the discovery of the MJO was influenced by Professor Yanai’s observational identification of equatorial waves (section 2). We then review Professor Yanai’s direct contributions to MJO research. These include the vertically integrated moist static energy budget and its development from moisture and heating profiles (section 3), cumulus momentum transport (section 4), eddy available potential and kinetic energy budgets (section 5), and tropical–extratropical interactions (section 6). The legacy of MJO research carried on by Professor Yanai’s students is discussed in section 7. Concluding remarks follow in section 8.

2. The discovery of the MJO by Roland Madden and Paul Julian

Professor Yanai’s early work was highly influential in the discovery of the MJO by Roland Madden and Paul Julian in the early 1970s. In a quest to explain the tropical quasi-biennial oscillation (QBO; e.g., Reed et al. 1961), Yanai and Maruyama (1966) documented the existence of short-time-scale variations in stratospheric wind at sounding stations in the west Pacific Ocean during March through July of 1958. These westward-propagating disturbances of 4–5 days and approximately $23 \text{ m s}^{-1}$ phase speed were subsequently shown by Maruyama (1967) to be associated with the mixed Rossby–gravity waves, alternately called Yanai waves, of equatorial shallow-water wave theory (Matsuno 1966). These disturbances were examined in more detail by Yanai et al. (1968). It was this latter paper that particularly inspired Roland Madden and Paul Julian to undertake the work that led to the MJO discovery.

The discovery of Yanai waves is discussed in more detail in chapter 3 of this monograph volume (Takayabu et al. 2016, chapter 3). In short, Yanai et al. (1968)
computed power spectra and conducted an analysis of spectral coherence for winds at 17 radiosonde stations in the west Pacific during April–July 1962. Spectra were examined at vertical levels from the surface to 25 km, including an analysis of the horizontal and vertical structures of the waves as they propagated across the west Pacific. Madden and Julian were motivated by this work because of the analysis techniques and the scientific content. First, they were highly inspired by the refined spectral analysis employed by Yanai et al. (1968). Roland Madden noted that the Yanai et al. (1968) analysis was impressive “in that they used cross-spectrum analysis every which way to identify wave structures” (R. Madden 2010, personal communication). Roland Madden also mentioned that they were “very much influenced by that [analysis] and used many of the spectral techniques to come up with the 40–50 day structure” in their work of Madden and Julian (1971; 1972) that first documented the MJO.

The scientific findings contained in Yanai et al. (1968) also provided impetus for the MJO discovery. Roland Madden recalled “it was also that paper that reported results for the 1962 period that I could not reproduce from the Line Islands experiment (spring of 1967), and so we became interested in the time-varying characteristics of the tropospheric waves” (R. Madden 2010, personal communication). Motivated to study the nonstationarity of the signal, Madden and Julian conducted an initial investigation using 10 years of radiosonde data from Canton Island (3°S, 172°W) in the Pacific. Roland Madden noted that although the initial purpose of their work was to examine high-frequency tropospheric wave signals, “we got distracted from that work when we saw the large 40–50 day signal” (R. Madden 2010, personal communication). This 40–50-day spectral peak was documented by Madden and Julian (1971), and similar periodicities were also discovered at other radiosonde stations within the tropical belt (Madden and Julian 1971, 1972). The analyses of spectral coherence pioneered by Professor Yanai inspired Madden and Julian to diagnose canonical MJO structure and evolution (Fig. 4-1; Madden and Julian 1972). This remarkable figure from Madden and Julian (1972) still represents our basic understanding of MJO structure today. Roland Madden finally noted that the late 1960s and early 1970s in which the MJO was discovered “were very interesting times for me, and I know that Yanai’s work was influential” (R. Madden 2010, personal communication).

Professor Yanai was one of the early users of methods for decomposing tropical variability in the wavenumber–frequency domain (Zangvil and Yanai 1981), which were developed for use in the tropical meteorology several years earlier by Professor Yanai’s student Yoshikazu Hayashi at the University of Tokyo and others (Hayashi 1973; Gruber 1974; Zangvil 1975). The mixed Rossby–gravity wave or Yanai wave was the featured disturbance in the initial applications of these techniques (Hayashi 1973). Subsequent work using wavenumber–frequency decomposition of the tropical atmosphere has uncovered important dynamical insights on the MJO (Wheeler and Kiladis 1999), including the clear spectral gap between
the MJO and convectively coupled Kelvin waves in wavenumber–frequency space (see chapters 3 and 6 of this monograph volume).

3. The moist static energy budget and its role in recent MJO theories

Yanai et al. (1973) developed a framework for calculating the vertically integrated moist static energy (MSE) budget starting from expressions for the apparent heat source ($Q_1$) and apparent moisture sink ($Q_2$), which has subsequently been used to provide profound insights into MJO dynamics. The more complete development of $Q_1$ and $Q_2$ in Yanai et al. (1973) follows initial introduction of these quantities in Yanai (1961), which provided an analysis of Typhoon Doris. Johnson et al. (2016, chapter 1) provide further details on this earlier development. As defined in Yanai et al. (1973) and elsewhere, the apparent heat source is

$$Q_1 = \frac{\partial \theta}{\partial t} + \mathbf{v} \cdot \nabla \theta + \bar{\omega} \frac{\partial \theta}{\partial p}$$

$$= Q_R + L\left(\mathbf{t} - \mathbf{v}\right) - \mathbf{v} \cdot \left(\nabla \mathbf{t}\right) - \bar{\omega} \frac{\partial \omega}{\partial p}, \quad (4-1)$$

where $s = c_p \theta + gz$ is the dry static energy, $\theta$ is the pressure velocity, $\omega$ is the horizontal wind vector, $Q_R$ is radiative heating, $L$ is latent heat of vaporization, $c$ represents condensation, and $e$ represents evaporation. Overbars represent a large-scale area average, and primes represent a deviation from that average. In (4-1), Yanai et al. (1973) excluded terms representing latent heating due to deposition, sublimation, freezing, and melting, which are generally much smaller than the other terms. Similarly, the apparent moisture sink can be defined as follows:

$$Q_2 = -L \left(\frac{\partial \theta}{\partial t} + \mathbf{v} \cdot \nabla \theta + \bar{\omega} \frac{\partial \theta}{\partial p}\right)$$

$$= L\left(\mathbf{t} - \mathbf{v}\right) - LV \cdot (\mathbf{v} \nabla \theta) + L \frac{\partial q \omega}{\partial p}. \quad (4-2)$$

where $q$ is the water vapor mixing ratio. Subtracting (4-2) from (4-1), and then doing a mass-weighted integral over the troposphere ($g^{-1}$ times the integral from the surface pressure to the tropopause pressure), one can show as in Yanai et al. (1973) that

$$\langle Q_1 \rangle - \langle Q_2 \rangle = \left\langle \frac{\partial \bar{\theta}}{\partial t} + \left(\mathbf{v} \cdot \nabla \bar{\theta}\right) + \bar{\omega} \frac{\partial \omega}{\partial p} \right\rangle$$

$$= \langle Q_R \rangle + LH + SH, \quad (4-3)$$

where $h = c_p T + gz + Lq$ is the MSE or moist entropy, LH is the surface latent heat flux, and SH is the surface sensible heat flux. Angled brackets represent a mass-weighted vertical integral. The right-hand side of (4-3) represents sources and sinks of moist entropy. Terms A, B, and C are the vertically integrated tendency of $h$, horizontal advection of $h$, and vertical advection of $h$, respectively. Yanai et al. (1973) and Yanai and Johnson (1993) noted that (4-3) is able to provide profound insight into diabatic heating processes in the tropics, and can be used to check the accuracy of tropospheric budgets given surface flux information.

Far-reaching implications of (4-3) for the MJO may not have come until much later, however. Neelin and Held (1987) used (4-3) to develop a model for tropical upper-tropospheric divergence as a proxy for deep convection. Assuming a first baroclinic mode structure to the tropical atmosphere, Neelin and Held (1987) were able to rewrite the vertical advection term in (4-3) as a quantity called “gross moist stability (GMS)” ($M_h$) times the vertically integrated lower-tropospheric mass convergence. In essence, $M_h$ represents the column-integrated MSE export per unit convective activity (Raymond et al. 2009), where in Neelin and Held (1987) convective activity was represented by mass convergence in the lower half of the troposphere (or similarly, mass divergence in the upper troposphere). In Neelin and Held (1987), $M_h$ was lowest over warm SST regions of the tropics because of higher lower-tropospheric humidity and greater moisture convergence per unit convective activity there (with the normalized upper-tropospheric export being constrained by weak tropical dry static energy gradients and thus only weakly varying across the tropics for the same mass flux profile; Charney 1963). Hence, convective activity is predicted by the Neelin and Held model to be enhanced in warm SST regions, since convection is less efficient at removing surface moist entropy sources from the column there. It has subsequently been shown that GMS is strongly regulated by vertical structure of diabatic heating (Peters and Bretherton 2006), suggesting that the first baroclinic mode structure of Neelin and Held (1987) should be relaxed. Gross moist stability was later generalized to also include horizontal advection (Raymond and Fuchs 2009).

Use of the column MSE budget to understand MJO dynamics has recently expanded. Under the assumption of weak tropical temperature gradients, which is a relatively good assumption at time scales of greater than 10 days that are characteristic of the MJO (e.g., Sobel and Bretherton 2000; Yano and Bonazzola 2009), (4-3) becomes an equation for the column-integrated moisture tendency because adiabatic cooling and diabatic heating to first order cancel to produce no net dry static energy tendency. Under such conditions, a class of balanced disturbances called moisture modes has been hypothesized to exist (Sobel et al. 2001; Raymond 2001;
Majda and Klein 2003; Maloney et al. 2010), in which gravity wave adjustment plays no role in propagation, and understanding the moisture (or MSE) budget is essential to understanding the basic maintenance and propagation of the modes. This former point distinguishes moisture modes from disturbances of equatorial shallow-water theory that are dependent on gravity for propagation, including Kelvin waves (e.g., Matsuno 1966). The strong link between tropical convection and column-integrated water vapor that has been demonstrated in observations is a key precept of moisture propagation, including Kelvin waves (e.g., Matsuno 1966). The strong link between tropical convection and column-integrated water vapor that has been demonstrated in observations is a key precept of moisture mode theory (e.g., Bretherton et al. 2004). Thus, (4-3) has been recently used to provide insights into the fundamental dynamics of the MJO, under the assumption that the MJO behaves like a moisture mode. This hypothesis is supported by the results of Wheeler and Kiladis (1999), which show a spectral gap between the MJO and convectively coupled Kelvin waves, and suggests that the MJO is not regulated by adjustment under gravity (see also Takayabu et al. 2016, chapter 3; chapter 6). Using (4-3) provides advantages over the moisture budget for diagnosing MJO dynamics, as it implicitly accounts for the cancellation of condensation and moisture convergence, which dominates the column-integrated MJO moisture budget.

Recent studies have used the MSE budget (4-3) to diagnose the mean state that global models must have to produce strong intraseasonal variability. In particular, models with high mean GMS tend to produce significantly weaker intraseasonal variability than those with lower GMS (e.g., Raymond and Fuchs 2009; Hannah and Maloney 2011), indicating that convection in these models is possibly too efficient at discharging column moisture, which makes it difficult to sustain moisture anomalies that are the key to MJO maintenance. In addition to the mean state diagnosis, recent studies have employed the MSE budget to diagnose fundamental internal dynamics of the MJO. In both observations (Haertel et al. 2008) and models (Hannah and Maloney 2011), shallow heating in advance of an MJO convective event has been shown to contribute to the buildup of column MSE. This is a state of negative GMS in which the net effects of shallow convection and associated divergent circulations act to moisten the column. Shallow convection has been previously hypothesized to be an important agent in moistening the column in advance of deep MJO convection (e.g., Benedict and Randall 2007). Further, horizontal MSE advection has been cited as an important regulator of eastward propagation (Maloney 2009; Maloney et al. 2010; Kiranmayi and Maloney 2011a; Andersen and Kuang 2012), including a potentially important role for intraseasonal variations in synoptic eddy activity for regulating the column MJO moisture budget through their effects on horizontal MSE advection (Maloney 2009; Andersen and Kuang 2012). Also, recent MSE budget analyses in observations and general circulation models (GCMs) have suggested that surface flux anomalies and cloud radiative feedbacks may be important destabilization mechanisms for the MJO (Lin and Mapes 2004; Maloney 2009; Kiranmayi and Maloney 2011a), with such inferences being verified with appropriate mechanism denial experiments in general circulation models (Sobel et al. 2008, 2010; Kiranmayi and Maloney 2011b; Andersen and Kuang 2012). Finally, semiempirical MJO models have been developed that use information on the vertically integrated MSE budget from observations and GCMs to demonstrate the basic dynamics of the MJO in an idealized framework (Sobel and Maloney 2012, 2013). In summary, the budget in (4-3) derived by Yanai et al. (1973) has proven to be a powerful tool in understanding MJO dynamics in both observations and models.

4. Cumulus momentum transport

One of the exemplary aspects of Professor Yanai’s work on the MJO was the gained understanding of cumulus momentum transport (CMT) during TOGA COARE and its role in maintaining the MJO low-level westerly flow. As will be discussed in more detail below, vertical transport of momentum by cumulus convection has the potential to significantly modulate the wind at different levels of the atmosphere. The strong near-surface westerly flow near and to the west of MJO convection has been hypothesized to be strengthened by such transports (e.g., Tung and Yanai 2002a). To precisely quantify the role of convective vertical momentum transport in the MJO and other convectively coupled disturbances is an extremely difficult endeavor, particularly in observational data.

Using data from the TOGA COARE inner flux array (IFA), Tung and Yanai (2002a) defined the residual ($\mathbf{X}$) of the IFA averaged momentum budget as follows:

$$
\mathbf{X} = \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \omega \frac{\partial \mathbf{v}}{\partial p} + \nabla \phi + \lambda \mathbf{k} \times \mathbf{v} = -\frac{\partial}{\partial p} \left( \nabla \mathbf{v} \cdot \mathbf{\omega} \right),
$$

(4-4)

where $\lambda$ is the Coriolis parameter, $\phi$ is the geopotential, overbars represent a large-scale area average, and primes are the deviation from this average. In (4-4), the area-averaged horizontal eddy flux divergence is assumed to be negligible. Therefore, the residual of the averaged areal budget $\mathbf{X}$ is ascribed to be due to the vertical eddy momentum flux convergence $-\frac{\partial}{\partial p} \left( \nabla \mathbf{v} \cdot \mathbf{\omega} \right)$.
thus including the effects of CMT. A strong correspondence in spectral power between brightness temperature (a proxy for deep convection) and $X$ during the TOGA COARE period supports the inference that the residual represents the effects of CMT (Tung and Yanai 2002a). The results of this spectral analysis and the wavelet analysis of Tung and Yanai (2002b) also suggest interesting multiscale interactions between the MJO and higher-frequency synoptic disturbances.

Figure 4-2 from Tung and Yanai (2002a) shows the evolution of wind fields, $Q_1$, and rainfall rate during the TOGA COARE period of November 1992 through February 1993. Two well-defined MJO events and associated strong low-level westerly flow transited through
the TOGA COARE IFA. In Tung and Yanai (2002a) the time mean residual in (4-4) over the TOGA COARE period suggests that on average cumulus convection acts to decelerate the flow, and CMT is downgradient. However, the same is not true in a time-varying sense, as was also suggested by studies on individual convective features during TOGA COARE (e.g., Lewis et al. 1998; Roux 1998; Bousquet and Chong 2000).

To highlight this time variability in the sign of CMT, Fig. 4-3 from Tung and Yanai (2002b) shows the evolution of the zonal wind, momentum budget residual \( \mathbf{X} \), \( Q_1/c_p \), and precipitation (gray circles) and a convective index derived from brightness temperature (gray bars) for part of the TOGA COARE IOP spanning the first MJO event from Tung and Yanai (2002b). Units are as in Fig. 4-2 and \( \mathbf{X} \) is in m s\(^{-1}\) day\(^{-1}\). Hatched regions in (a) and (b) represent unreliable data.
13–21 December 1992 is of the same order of magnitude as the zonal wind acceleration, indicating a likely role of CMT for accelerating the low-level westerly flow during this MJO event. Downgradient momentum transport ensued after 21 December when the MJO westerly wind burst was mature. While of smaller amplitude, similar processes appeared to act during the second TOGA COARE MJO event of late January through early February 1993 (not shown). Tung and Yanai (2002b) argued that shallow convection or squall lines are integral to the upgradient momentum transport at the onset of the westerly wind burst associated with both of these MJO events, and such effects may have profound implications for convective parameterizations and their ability to properly simulate the MJO, since most convection parameterizations neglect the possibility of such upgradient momentum transport (e.g., Moncrieff 2004). While other studies using other datasets over longer periods (e.g., Lin et al. 2005) or different analysis techniques during the TOGA COARE period (e.g., Houze et al. 2000) have suggested a lesser role for upgradient momentum transport for supporting the flow at the westerly onset phase, the results of Tung and Yanai (2002b) have proven extremely influential for spawning a body of theoretical work on the MJO over the subsequent decade.

In the theoretical work of Majda and Biello (2004), upscale transfer of kinetic and thermal energy from wave trains of tropical synoptic-scale disturbances (e.g., superclusters; Nakazawa 1988) are necessary to maintain the large-scale MJO flow in the presence of synoptic disturbances that tilt westward with height, a paradigm also proposed by the work of Moncrieff and Klinker (1997). Superclusters refer to eastward-propagating envelopes of convection, shown by Nakazawa (1988) to most often be convectively coupled Kelvin waves. Related work by Moncrieff (2004) also documented the importance of vertically tilted mesoscale organization for supporting the large-scale MJO flow. Such ideas have been expanded in subsequent work to develop refined models of the MJO that involve multiscale interactions. Biello and Majda (2005) accounts for the evolution of convective organization during MJO events from congestus in the eastern part of the MJO convective envelope (with assumed eastward tilts with height) to supercluster-like structure in the western part (with assumed westward tilts with height) to produce a more realistic large-scale flow than in Majda and Biello (2004). Such assumptions on where particular wave types maximize relative to the MJO convective envelope and their respective tilts with height, which depend on the propagation direction, have since garnered further observational support (e.g., Kikuchi and Wang 2010). Majda and Stechmann (2009a) use a simple dynamical model with imbedded multicloud parameterization (of Khouider and Majda 2006) that is able to simulate two-way interactions between the convectively coupled equatorial waves and the large-scale MJO flow to demonstrate that both the upgradient momentum transport observed at the initiation of the TOGA COARE westerly wind bursts and the subsequent downscale momentum transport observed by Tung and Yanai (2002b) can be captured by such a model. Work with this model was extended in Han and Khouider (2010) and Khouider et al. (2012) to show that the predominant type of convectively coupled wave produced as a function of MJO regime could be accurately captured, with the implications for upscale momentum transport for MJO dynamics also discussed.

Another important study in this line of research is that of Majda and Stechmann (2009b). This study provides a theory for both the propagation dynamics and instability mechanism of the MJO. The MJO “skeleton” is a simple Matsuno–Gill type dynamical model that without explicit synoptic-scale momentum fluxes and their effect on the MJO flow would be in a neutral state. A parameterized envelope of synoptic-scale wave activity provides the “muscle,” and hence instability mechanism. The instability mechanism is assumed to involve multiscale interactions with the synoptic scale that provide upscale momentum and energy transports to maintain the large-scale MJO circulation against dissipation. Such upscale transport is parameterized in terms of the envelope of synoptic-scale wave activity. The envelope of synoptic activity serves as the heating source as well as the moisture sink through precipitation, and its temporal behavior depends on low-level moisture. With an assumed equatorially trapped meridional structure, this envelope of synoptic-scale wave activity generates the Kevin and gravest Rossby waves, which form the base function to construct the MJO. The model yields a dispersion relationship, from which a nondissipative MJO frequency is obtained. The MJO solution also includes slow (5 m s$^{-1}$) propagating quadrupole vortices surrounding the envelopes of synoptic-scale wave activity, interpreted as the MJO convective envelope. This model has subsequently been used to examine its nonlinear behavior in the presence of different basic states, including a uniform SST distribution and one with a warm pool, and is able to capture other salient features of the MJO including its observed irregularity (Majda and Stechmann 2011). This model was expanded to include a frictional boundary layer that appears to improve upon the realism of the simulated MJO and aid in the selection of eastward-propagating modes (e.g., Wang and Liu 2011; Liu and Wang 2013), with the ability of synoptic-scale disturbances to destabilize the MJO
dependent on where particular wave types occur relative to the MJO convective envelope (as discussed above).

Besides the theoretical work discussed above, studies with more complex models have supported the importance of CMT to the dynamics of the MJO. Deng and Wu (2010) employed a CMT parameterization that accounts for the vertical redistribution of momentum by convection as well as the effect of the perturbation pressure field generated by the interaction of the large-scale flow with convection (e.g., Wu and Yanai 1994). They demonstrated that this scheme leads to stronger, more coherent MJO convection. Specifically for the western Pacific, Deng and Wu (2011) showed that inclusion of this CMT parameterization contributed to strengthening the westerly wind phase of the MJO. Zhou et al. (2012) demonstrated that inclusion of a CMT parameterization in a version of the NCAR Community Atmosphere Model has the beneficial effect of improving the simulation of low-level westerly mean winds in the Indo-Pacific warm pool, which produces an improved simulation of intraseasonal variability. Miyakawa et al. (2012) used a global nonhydrostatic model to show that CMT helps to accelerate the westerly surface flow during MJO events, possibly reducing the eastward propagation speed of events as well as reducing momentum damping influence of the large-scale flow. Finally, “superparameterized” modeling approaches with some aspects of convective momentum transport explicitly simulated are able to produce improved intraseasonal variability (e.g., Grabowski 2002). The concept of superparameterization is discussed in extended detail in Randall et al. (2016, chapter 15).

5. Energy budgets

In a pair of papers, Yanai et al. (2000) and Chen and Yanai (2000) documented the basic characteristics of MJO events during the TOGA COARE IOP and for a longer 15-yr climatology, and then computed perturbation available potential energy (PAPE) and perturbation eddy kinetic energy (PKE) budgets to determine the dominant processes that help to maintain the large-scale MJO circulation against dissipation. In general, the TOGA COARE MJO events were found to be representative of behavior in the extended period, with a few exceptions, including the stronger variability during TOGA COARE as compared to the longer record, especially in the central Pacific near the date line. A few other interesting observations from Yanai et al. (2000) on MJO behavior during the TOGA COARE period will be discussed below.

Both Yanai et al. (2000) and Chen and Yanai (2000) computed detailed PAPE and PKE budgets using European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis products, deriving $Q_1$ as a residual of the thermodynamic energy equation for use in the PAPE budget. By far the largest source of PKE in the Indo-Pacific warm pool is associated with conversion of PAPE to PKE in the middle troposphere (Fig. 4-4a), with a resulting geopotential energy flux that moves energy upward and downward supporting PKE maxima in the upper and lower troposphere (not shown). PAPE generation is predominantly due to the covariance of diabatic heating and temperature perturbations (not shown), which is nearly cancelled by PKE conversion from PAPE. This cancellation is consistent with the dominant thermodynamic balance of diabatic heating and adiabatic cooling that associated with weak temperature gradient theory for the tropical atmosphere (e.g., Sobel and Bretherton 2000). The domination of Indo-Pacific warm pool MJO energy conversion processes by diabatic heating provides evidence for the idea of the convectively coupled nature of the MJO and is supported by previous and subsequent analysis (e.g., Hendon and Salby 1994; Mu and Zhang 2006; Deng and Wu 2011). Diabatic heating is also the primary energy source for large-scale motions associated with the boreal summer intraseasonal variability that occurs in the east Pacific warm pool (Maloney and Esbensen 2003). Interestingly, Yanai et al. (2000) documents a minimum in PAPE generation by diabatic heating in the Maritime Continent region, which contains a well-documented minimum in 30–60-day convective variability there (e.g., Zhang and Hendon 1997; Sobel et al. 2010).

As noted by Yanai et al. (2000), Chen and Yanai (2000), and other studies, the PKE maximum associated with the MJO actually occurs in the upper troposphere in the east Pacific just to the west of South America. This is an upper-tropospheric westerly duct region where strong tropical–extratropical interactions take place, and convective activity is a minimum (e.g., Webster and Holton 1982; Magaña and Yanai 1991). The budget analysis by Yanai et al. (2000) and Chen and Yanai (2000) shows that barotropic energy conversions and an equatorward flux of extratropical/subtropical wave energy are the dominant terms supporting the strong MJO flow in this region (Figs. 4-4b,c), which helps to explain the large PKE maximum there in the absence of diabatic heating.

The discussion section of Yanai et al. (2000) provides very interesting insights on priorities for future MJO research. For one, it is noted that a holistic view of coupling between different vertical heating modes (as defined by $Q_1$ and $Q_2$) and the large-scale MJO flow is a priority. This quest underlies many of the research areas discussed above, including the impact of higher vertical
FIG. 4-4. (a) PAPE to PKE conversion, (b) barotropic conversion, and (c) horizontal convergence of wave energy flux in the 30–60-day band during the TOGA COARE experiment from Yanai et al. (2000). Units are J kg$^{-1}$ day$^{-1}$ with negative values shaded gray.
heating modes in the moistening/drying process during an MJO life cycle (e.g., Haertel et al. 2008), and the tilted vertical structure of the MJO and the consequences for the horizontal momentum budget (e.g., Moncrieff 2004). Tung et al. (1999) suggested that three coupled modes of $Q_1$ and $Q_2$ are needed to describe heating and moistening under different large-scale convective phases of the MJO during TOGA COARE that include the convectively active phase of the MJO with heavy precipitation, the light to moderate precipitation period prior to the active phase, and the period after the MJO convective peak with strong surface wind and enhanced surface evaporation. In the same spirit, Zhang and Hagos (2009) derived two leading modes from sounding-based $Q_1$. The first leading mode peaks at about 400 hPa and the second at 700 hPa. Together they account for almost all structural variability of diabatic heating during TOGA COARE. These two leading modes suggest the importance of shallow as well as deep convective heating to the MJO. Yanai et al. (2000) also foreshadows the Dynamics of the MJO (DYNAMO) program during 2011–12, a field campaign designed to study MJO initiation processes (Yoneyama et al. 2013). Yanai et al. (2000) note the origination of super cloud clusters during the TOGA COARE time period near 75°E, a longitude that intersects the two DYNAMO sounding arrays. In particular, the analysis of Yanai et al. (2000) notes the possibility of superclusters near 75°E being triggered by precursor activity that first appears in upper-tropospheric wind and temperature anomalies coming from the west, possibly in association with the previous MJO event. The origin of the second MJO event during TOGA COARE can be followed back to the Western Hemisphere, at 40°W. Yanai et al. (2000) thus appear to have documented an example of “successive” MJO events, a term later coined by Matthews (2008) when describing different types of MJO initiation that also include “primary” events. The $Q_1$ estimation for the MJO by Yanai et al. (2000) provides a background for a model intercomparison project on the vertical structure and physical processes of the MJO, with an emphasis on its diabatic heating profiles (Zhang et al. 2013).

6. Tropical–extratropical interaction

In a series of studies, Yanai and his colleagues documented connections between equatorial wave activity and equatorward energy and momentum fluxes from the extratropics, laying the observational foundation for later work in the area of extratropical influences on equatorial waves and associated moist convection as modulated by the MJO. Zangvil and Yanai (1980) performed time–space spectrum analyses on a 200-hPa wind dataset for the period of 1 June–31 August 1967. Using a method proposed by Yanai and Murakami (1970) that decomposes the wind field into symmetric and antisymmetric components with respect to the equator, they identified Kelvin waves (zonal wavenumber $k = 1–2$, period $\tau = 7$ days, and $k = 1$, $\tau > 20$ days), mixed Rossby–gravity waves ($k = 4$, $\tau = 5$ days), and $n = 1$ Rossby waves ($k = 2$, $\tau = 12$ days) from their data. They further calculated the meridional flux of wave energy due to pressure work, which propagates freely into the tropics in the east and central Pacific and Atlantic where no critical latitude exists (see also Fig. 4-6 and Knippertz 2007). Influence of this wave energy is concentrated at the zonal wavenumbers and periods of mixed Rossby–gravity waves. This analysis suggested that the mixed Rossby–gravity waves could be excited by lateral forcing from a higher latitude. The work of Zangvil and Yanai (1980) was extended by Yanai and Lu (1983) by including additional data during June–August 1972. The year 1972 differed from 1967 since mixed Rossby–gravity waves were absent and weak Kelvin and Rossby waves were present. The absence of the mixed Rossby–gravity waves was associated with a peak of meridional wave energy divergence in the tropics at characteristic wavenumbers and periods of the waves, instead of wave energy convergence as observed in 1967. Meridional wave energy convergence in the tropics, on the other hand, was observed at the wave-numbers and periods of Rossby waves. The work of Zangvil and Yanai (1980) and Yanai and Lu (1983) provided the first observational evidence for the effect of the east Pacific “westerly duct” (Webster and Holton 1982) on equatorial waves and the motivation for later theoretical explanations of laterally forced equatorial waves (Zhang and Webster 1992; Zhang 1993; Hoskins and Yang 2000). Zangvil and Yanai (1981) used satellite observations to relate mixed Rossby–gravity wave signals to tropical convection, which was one of the earliest observational studies on “convectively coupled equatorial waves.” The extension of Yanai’s work on tropical–extratropical interaction from synoptic to intraseasonal time scales, discussed in detail below, paved the way for later efforts that identified extratropical influences on equatorial waves in different phases of the MJO, also discussed later in this section.
analysis to characterize the nature of such interactions. Of particular interest is that during 1979 the MJO produced substantial variations in the amplitude of the upper-tropospheric mid-Pacific trough and Mexican anticyclone as it progressed eastward. The mid-Pacific trough was amplified in the presence of enhanced convection in the far west Pacific and suppressed convection in the central Pacific, enhancing the thermal contrast between Asia and the central North Pacific. Associated upper-level convergence in the central Pacific also strengthened the trough. Related processes occurred in the Americas, where enhanced convection and associated upper-tropospheric divergence of the MJO strengthened the Mexican anticyclone. The extension of boreal summer convection associated with the MJO during 1979 to the Americas as noted in Magaña and Yanai (1991) is interesting, especially the tendency for convection near the Mexican coast to be out of phase with that to the west of 120°W. While similar signals did appear in previous composite life cycles of the MJO (e.g., Knutson and Weickmann 1987), a larger body of work has since developed that examines how the MJO influences precipitation, winds, tropical cyclone activity, and other variables in the east Pacific warm pool during boreal summer (e.g., Maloney and Hartmann 2000; Molinari and Vollaro 2000; Barlow and Salstein 2006; Jiang et al. 2012). Recent analysis using regional and global models suggests that intraseasonal variability in this region can exist in isolation from Eastern Hemisphere MJO variability, but likely phase locks given common dominant periodicities (Rydbeck et al. 2013). Magaña and Yanai (1991) were pioneers in the study of intraseasonal variability in the east Pacific region.

Fluctuations in the mid-Pacific trough on intraseasonal time scales are associated with northward propagation of angular momentum anomalies in the North Pacific, as documented in the time series of 200-hPa zonal wind anomalies (raw and bandpass filtered) at different latitude belts from Magaña and Yanai (1991; Fig. 4-5). Such fluctuations in extratropical wind anomalies associated with tropical intraseasonal variability were also noted in other previous studies (Liebmann and Hartmann 1984; Weickmann et al. 1985; Lau and Phillips 1986; Knutson and Weickmann 1987), and the global angular momentum balance associated with the MJO has in particular been a topic of much attention over the last four decades (e.g., Madden 1987; Kang and Lau 1990; Weickmann et al. 1992; Weickmann and Sardeshmukh 1994; Madden and Speth 1995; Weickmann et al. 1997).

Magaña and Yanai (1991) also argued that intraseasonal fluctuations in the mid-Pacific trough, in addition to being associated with intraseasonal fluctuations of angular momentum, could also cause variations in the strength and spatial extent of the upper-tropospheric equatorial westerly duct that could admit or suppress penetration of extratropical Rossby wave energy into the tropics. The dominant pathway of such energy transport is shown in Fig. 4-6, which displays E vectors at 200 hPa for the total (Fig. 4-6a), the 30–60-day (Fig. 4-6b), and high-frequency (Fig. 4-6c) eddy fields. The barotropic E vector was defined by Magaña and Yanai (1991) using the formalism of Trenberth (1986) as

$$E = \frac{1}{2} \left( \overline{\nu^2} - \epsilon^2 \right), -\overline{\nu'w'} \cos \phi.$$

Here, primes represent temporal eddies, bars represent the time mean, and \( \phi \) is latitude. This vector represents the direction of the eddy group velocity, and \(-E\) is equivalent to a westerly eddy momentum flux (e.g., Hoskins et al. 1983; Trenberth 1986). Figure 4-6 indicates a notable...
FIG. 4-6. The $E$ vectors (m$^{-2}$s$^{-2}$) computed for (a) total anomaly field, (b) 30–60-day filtered fields, and (c) fields filtered to less than 30 days for the summer of 1979. The mean 200-hPa zonal wind is shown in contours with an interval of 10 m s$^{-1}$. From Magaña and Yanai (1991).
southwestward energy flux in the central equatorial Pacific in the area of the mid-Pacific trough. Magaña and Yanai (1991) noted that this flux is strengthened during strengthening of the mid-Pacific trough, when the westerly duct is enhanced during MJO events. Consistent with the discussion in Magaña and Yanai (1991), other studies have documented that convection in the central and east Pacific is preferentially induced in the presence of a westerly upper-tropospheric basic state when strong tropical–extratropical interactions occur (e.g., Kiladis and Weickmann 1992).

Pacific tropical–extratropical interactions and implications for convectively coupled wave activity as modulated by the MJO have been examined in more detail since the Magaña and Yanai (1991) work. Magaña and Yanai (1995) argue that a westerly or weak easterly basic state in the equatorial east Pacific upper troposphere and a favorable spatial and temporal structure and amplitude of extratropical forcing are particularly efficient at generating equatorial mixed Rossby–gravity waves. The MJO is effective at forcing variations in the strength and direction of the upper-tropospheric flow in the east Pacific that can affect mixed Rossby–gravity wave generation. Matthews and Kiladis (1999) show that during Northern Hemisphere winter in a phase when MJO convection is enhanced over the east Indian Ocean and Maritime Continent and suppressed over the South Pacific convergence zone, upper-tropospheric transients emanating from a source region in the Asian jet can penetrate more effectively into the central Pacific because of relaxation of the upper-tropospheric easterly basic state. Enhancement of high-frequency transients on 6–25-day time scales in the central Pacific results, with further rectification onto the MJO time scale (see also Meehl et al. 1996). In this context, rectification means that since precipitation is a positive definite quantity, transient activity is associated with a nonlinear precipitation signal that can project onto longer MJO time scales. Straub and Kiladis (2003a) examine the interactions of the boreal summer version of the MJO and convectively coupled mixed Rossby–gravity and Kelvin waves and demonstrate an enhancement of Kelvin wave activity to the east of the MJO convective center over the central Pacific, consistent with the hypothesis of Magaña and Yanai (1991). Straub and Kiladis (2003a) also argued for a strong mutual interaction between mixed Rossby–gravity waves and the MJO in the enhanced convective region of the MJO. Straub and Kiladis (2003b) documented a pathway by which extratropical Rossby wave trains in the Southern Hemisphere could penetrate toward the equator and initiate Kelvin wave activity in the central and east Pacific ITCZ, a process presumably enhanced during phases of the MJO when the upper-tropospheric background flow is favorable. Such a pathway is also suggested in the bottom panel of Fig. 4-6 from Magaña and Yanai (1991) and in Fig. 10 of Magaña and Yanai (1995). The importance of tropical–extratropical interactions to the MJO has been pursued over the last few decades in observational studies (Lau and Peng 1987; Hsu et al. 1990; Lau et al. 1994; Matthews et al. 1996; Straus and Lindzen 2000), theoretical work (Meehl et al. 1996; Frederiksen and Frederiksen 1997), and numerical modeling studies (Lin et al. 2007; Ray et al. 2009; Ray and Zhang 2010; Ray and Li 2013).

7. The legacy continued by Professor Yanai’s students

Perhaps his students, who have pushed and continue to push the boundaries of our MJO understanding, carry on Dr. Yanai’s most enduring legacy to MJO research. Their seminal contributions have continued beyond those in direct collaboration with Professor Yanai. Dr. Tatsushi Tokioka has conducted seminal research on cumulus parameterization, including development of the famous “Tokioka modification” to deep convection parameterizations, which has led to substantial improvements in MJO simulations by climate models (Tokioka et al. 1988). Dr. Tsuyoshi Nitta demonstrated the role of intraseasonal oscillations and associated westerly wind bursts to the development of the 1986/87 El Niño event (Nitta et al. 1992), and also studied teleconnections associated with boreal summer intraseasonal convective variability in the western Pacific (Nitta 1987). Dr. Masato Murakami conducted an observational analysis of 30–40-day convective variability in Southeast Asia the western Pacific during boreal summer (Murakami 1984; Chen and Murakami 1988). Randall et al. (2016, chapter 15) discuss in more detail boreal summer intraseasonal variability in the context of superparameterization in climate models.

Dr. Steven Esbensen helped forge better understanding of the remote influence of the MJO on the Western Hemisphere, in particular the east Pacific warm pool during boreal summer (Maloney and Esbensen 2003, 2005, 2007). Study of the multiscale-scale structure of the MJO (Sui and Lau 1992), and work on air–sea interaction associated with the MJO during the TOGA COARE experiment (Sui et al. 1997; Lau and Sui 1997) were topics of study by Dr. Chung-Hsiung Sui. Dr. Victor Magaña conducted an observational analysis of 40–50-day variations in atmospheric angular momentum and length of day as a function of latitude (Magaña 1993). Dr. Xiaojing Wu has conducted observational, cloud-resolving model, and general circulation model studies to understand the
governing dynamics of the MJO, including its multiscale structure (Wu et al. 1998; Wu and LeMone 1999; Deng and Wu 2011). Dr. Baode Chen collaborated on modeling work that examined the importance of frictional convergence to the MJO (Chao and Chen 2001). Dr. Wen-Wen Tung continues seminal research on the multiscale structure of the MJO (Tung et al. 2004) and MJO predictability (Tung et al. 2011). Finally, Dr. Chih-Wen Hung has explored the relationship between the intraseasonal oscillation, Asian summer monsoon, and the mei-yu front (Hung and Hsu 2008), and also worked with Professor Yanai to examine the processes responsible for onset of the summer Australian monsoon, including the MJO (Hung and Yanai 2004). Through his students, Professor Yanai’s influence will likely continue to be felt for many future generations.

8. Concluding remarks

The legacy of Professor Yanai’s study of the MJO will be with us for many years to come. His pioneering analysis techniques, insightful research directions, and genuine support of young scientists have inspired a new generation of scientists in their studies of the MJO, including many of Dr. Yanai’s students and also the authors of this chapter. It should also be mentioned that Professor Yanai’s influence on MJO research was felt in other ways. The University of California, Los Angeles (UCLA), Tropical Meteorology and Climate Newsletter that was moderated by Professor Yanai provided a stimulating forum to discuss current MJO research in advance of formal peer review and publication. The authors took advantage of this newsletter whenever possible to introduce our latest MJO work to the tropical meteorology community.

While progress has been made in the past decades, our understanding of the MJO and our ability to simulate and predict it are still limited. Professor Yanai’s contributions to MJO research—especially in the context of heating and moistening profiles, cumulus momentum transport, energy budget and conversion, and tropics-extratropics interaction—will continue to benefit future MJO studies and model development.

Acknowledgments. We thank Roland Madden, Wen-Wen Tung, and Robert Fovell for their knowledge and advice during the writing of this manuscript. We would also like to thank George Kiladis and one anonymous reviewer for their thorough and constructive reviews of the manuscript. The authors acknowledge support from the National Science Foundation Climate and Large-Scale Dynamics Program under Grants AGS-1025584, AGS-1062161, AGS-0946911, and AGS-1441916 (EDM), as well as AGS-1062202 (CZ). We also acknowledge support from the NOAA MAPP program under Grant GC09-330a (CZ) and Contracts NA12OAR4310077 (GC12-433) and NA08OAR4320893 7,14 (EDM).

REFERENCES


Haertel, P. T., G. N. Kiladis, A. Denno, and T. M. Rickenbach, 2008: Vertical-mode decompositions of 2-day waves and the...


