This chapter distinguishes the mechanism of tropical convective disturbances, such as a hurricane, from that of the Madden–Julian oscillation (MJO). The hurricane is maintained by organized convection around the azimuth. In a hurricane the organization of convection, the generation of eddy available potential energy, and the transformation of eddy available potential energy into eddy kinetic energy all occur on the scale of the hurricane and these are called “in-scale processes,” which invoke quadratic nonlinearity. The MJO is not a hurricane type of disturbance; organized convection simply does not drive an MJO in the same manner. The maintenance of the MJO is more akin to a multibody problem where the convection is indeed organized on scales of tropical synoptic disturbances that carry a similar organization of convection and carry similar roles for the generation of eddy available potential energy and its conversion to the eddy kinetic energy for their maintenance. The maintenance of the MJO is a scale interaction problem that comes next, where pairs of synoptic-scale disturbances are shown to interact with a member of the MJO time scale, thus contributing to its maintenance. This chapter illustrates the organization of convection, synoptic-scale energetics, and nonlinear scale interactions to show the above aspects for the mechanism of the MJO.

1. Introduction

This study addresses the role of deep convection, nonlinear dynamics, and energetics for the maintenance of the Madden–Julian oscillation (MJO). The horizontal scale of the MJO is around 10,000 km. It is largely defined by zonal wavenumbers 1 and 2 (Madden and Julian 1971). This wave carries its largest amplitude over the equatorial latitudes and moves around Earth in roughly 20 to 60 days (Madden and Julian 1971; Krishnamurti and Gadgil 1985; Waliser et al. 2003). The amplitude of the zonal wind anomaly on this time scale is of the order of 1 to 3 m s$^{-1}$. The divergent wind on this time scale carries amplitude on the order of 1 m s$^{-1}$. A much cited illustration relating clouds to the MJO wave is the well-known Nakazawa diagram (Nakazawa 1988). An example is shown in Fig. 5-1. This illustration shows an active part of the MJO wave that carries a plethora of clouds. Multiple scales of clouds are present here. The mesoconvective cloud lines, embedded within the larger-scale MJO envelope wave, propagate from east to west with typical speeds on the order of 5° to 7° longitude per day whereas the MJO moves eastward around the globe (360°) in around 40 days. This disparity in space–time scales of the clouds and mesoscales embedded in synoptic scales and the planetary-scale MJO makes it an interesting problem for scale interactions. Basically the important question we raise here is how clouds whose scale is of the order of a few kilometers communicate with the MJO, which has a scale of around 10,000 km. Two types of energy exchanges that invoke quadratic or triple product nonlinearities are important in the context of scale interactions.

In modeling multiple scales of the MJO, Biello and Majda (2005) noted the importance of westerly and easterly regimes of flows and wave trains carrying tilted organized synoptic scales. That is consistent with our findings. Scale interactions among 2-day waves and moist Kelvin waves were examined by Liu and Wang (2012a), where they noted that the convergence of eddy momentum and heat transports were sensitive to the phase of westerly winds of the lower and the upper...
The role of friction was examined for the excitation of MJO by Liu and Wang (2012b), who noted a wavenumber dependence; that is, for long waves with wavenumbers less than 5, the Ekman pumping of moisture helped their growth from the moisture convergence. A formal study on scale interactions in the MJO was authored by Wang and Liu (2011), who noted that the eddy heat and moisture transports and their convergences arising from the passage of moist Kelvin waves was an important factor for

FIG. 5-1. Time–longitude section of temperature of black body (TBB; brightness temperature) index (ITBB) integrated between the equator and 5°N obtained from the 3-hourly Geostationary Meteorological Satellite (GMS) infrared data from 0000 UTC 29 May to 2100 UTC 10 Jul 1980. Symbols A to D denote the superclusters. The contour interval is 10 and shading denotes the region where values are >20 [adapted from Nakazawa (1988)].
the maintenance of the MJO. In recent years, a series of multiscale interaction mechanisms have been presented for the MJO. The upscale momentum transfer of superclusters can drive the MJO-like circulation (Majda and Biello 2004; Biello and Majda 2005; Wang and Liu 2011; Liu and Wang 2013). The wave activity of synoptic-scale disturbance acts as a heat/moisture source/sink or vice versa—that is, an oscillator for the MJO (Majda and Stechmann 2009; Liu and Wang 2012a, b). These studies are relevant for the overall understanding of the MJO. Our study addresses the in-scale and out-of-scale energetics as means for the understanding of the MJO.

We address these respective interactions using energy exchange equations to illustrate the role of organized convection in the maintenance of the mesoscale and synoptic scale and the role of nonlinear dynamics for the exchanges of energy from the synoptic and the MJO time scales.

Figure 5-2 shows a time–longitude Hovmöller diagram for the 200-hPa level velocity potential, on the time scale of the MJO (20–60 days), for the summer months of the year 1996. This is the year for which the scale interactions are computed. These are latitudinal averages between 10°S and 10°N. Positive values of the velocity potential denote regions from where divergent outflows at 200 hPa emanate. The amplitude of the divergent wind is largest in the Asian monsoon belt of India and East Asia as well as the western Pacific Ocean. Divergent winds are weaker over the Atlantic and east Pacific longitudes. The magnitude of the divergent wind at the 200-hPa level is between 1 and 4 m s\(^{-1}\) in the Asia–Pacific belt of the monsoon. The magnitude of the divergence, on the time scale of the MJO, is between 10\(^{-7}\) and 10\(^{-6}\) s\(^{-1}\). This weak divergence (and the compensating convergence of the lower troposphere) cannot account for the cloud scale or mesoconvective scales since the convergence/divergence is only on the order of 10\(^{-7}\) to 10\(^{-6}\) s\(^{-1}\). The passage of an active MJO at best can only initiate clouds; the subsequent growth of clouds requires a mesoscale forcing within synoptic-scale disturbances. The well-known Nakazawa diagram

![Figure 5-2](image-url)
(Fig. 5-1) shows an MJO envelope over the western Pacific Ocean. Within that envelope the synoptic-scale disturbances turn carry mesoscale convective cloud elements. Understanding this multiscale problem is central for the understanding the mechanism of the MJO.

The DYNAMO (Dynamics of the MJO) experiment in conjunction with other field experiments is aimed at collection of datasets for a better understanding of the MJO, its initiation, and its dynamics, as well as for improved prediction. There is clearly a need for such an observational experiment to better understand the role of convection in the maintenance and initiation of the MJO. The sounding radar array of DYNAMO is a vital component for such observations. Zhang et al. (2010) and Yuan and Houze (2013) are prominent contributors to the DYNAMO program. Zhang et al. (2010) have examined the heat sources for the MJO cycles and noted that both shallow convective and deep convective heating carry the MJO time scale signals over the western Pacific and the Indian Ocean regions. Lin et al. (2004) have also examined the heating profiles for the stratiform clouds during MJO passages. Yuan and Houze (2013) have examined the proportions of the total precipitation and cloud cover contributed by the MJO time scale. These are important for our overall understanding of the MJO.

The passage of the MJO from the tropical Pacific to the Atlantic has been succinctly described by Yu et al. (2011), who provide the background dynamics for the eastward motion of the MJO. The importance of moist convection for the MJO is well recognized (Hannah and Maloney 2011). That the MJO modulates tropical weather over the western Pacific has been well documented in their study. Recent studies of Zhang et al. (2010) and Ray et al. (2010) have examined important observational and modeling aspects of the MJO. They have examined the vertical distributions of heating and the structure of the MJO environment. Their findings support the importance of deep convection and its environment. Observational and modeling studies by many authors have provided major insights into the role of convection and the structure of MJO (e.g., Kikuchi and Wang 2010; Wang et al. 2009; Waliser et al. 2009; Liu et al. 2009, among others).

2. Organization of convection in synoptic disturbances

The energetics of a hurricane is a good example on the role of the organization of convection. When one performs such an energetics (e.g., Krishnamurti et al. 2003), for a hurricane the generation of eddy available potential energy by convective heating and the conversion of eddy available potential energy into eddy kinetic energy are noted to occur on large azimuthal scales in the inner core of hurricanes. That is a clear reflection that deep convection is organized on the large azimuthal scales. The tangential winds in the inner core of a hurricane show most of the variance for azimuthal wavenumbers 1 and 2. That defines the scale of the hurricane. Although the individual elements of deep convective clouds carry scale on the order of a few kilometers each, the organization as a whole, brought about initially by shear flow instabilities, places the cloud scale into these large azimuthal scales. The above aspects of the hurricane energetics are described in Krishnamurti et al. (2003).

The MJO waves that propagate from west to east beneath these waves are tropical disturbances such as the monsoon depressions of the Indian Ocean and tropical lows and depressions of the tropical Pacific Ocean. These disturbances carry somewhat similar energetics and organization of convection. The energetics of these depressions are relevant to the coupling of synoptic and the MJO time scales that are discussed in this study.
The generation and conversion of eddy available kinetic energy is largely described by covariances of heating and temperature and of vertical velocity and temperatures (Fig. 5-3); those are quadratic nonlinearities (i.e., in-scale processes in the vocabulary of scale interactions). This states that the generation and conversion, including the organization of clouds, all occur on the same scales (i.e., they are all in-scale processes). If clouds are organized along azimuthal wave-numbers L1, L2, L3, L4, etc., then all these processes will also occur in the same repetitive scales and no communication is permitted with scales outside of a scale. The governing principle is the trigonometric selection rule (called \( m = n \)) for such quadratic nonlinearities.

Ideally good radar coverage would portray the organization of convection around a monsoon depression; lacking that, the mapping of daily precipitation can provide a reasonable picture of this organization. Figure 5-4 shows four examples of the 850-hPa level streamlines and 24-h rainfall totals, centered around the map time, when an intense

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**Fig. 5-4.** Four cases of low pressure systems (lows) formed over the Indian region (7°–35°N, 60°–100°E) for (a) 20 Jul, (b) 21 Jul, (c) 8 Aug, and (d) 28 Aug 1996. The heavy lines identify regions where the processes shown above the diagram are prominent.
monsoon depression was present over India. These are rather typical maps of the flow field with superimposed rainfall. In all these illustrations, the organization of mesoconvective precipitating elements along the cyclonic streamlines of the monsoon depression is clearly evident. The typical rainfall intensities in these depressions are on the order of 50 mm day$^{-1}$. In the next section the Lorenz box energetics for these four examples are illustrated, relating the organization of convection to the eventual growth of eddy kinetic energy of the monsoon depression.

3. Lorenz box energetics on synoptic scales

The results of Lorenz box energetics are presented in this section. The synoptic-scale precipitating disturbances include tropical waves through the central Pacific Ocean and monsoon depressions over India. These were cases selected during the eastward passage of an active MJO wave (shown in Fig. 5-1) over the central Pacific and the Indian monsoon environment at the 200-hPa level. These cover the 1996 summer months. Figures 5-4 and 5-5 illustrate synoptic features for these tropical disturbances over the Indian and central Pacific regions respectively. These illustrations include the 850-hPa level streamlines and the superimposed rainfall fields. Around the quasi-circular geometry of the flow fields in these illustrations, an organization of convection is implied by these rainfall patterns. These include four separate synoptic cases for of these regions respectively. In all cases, we can see a synoptic-scale organization of the heavy rain elements. The box energetics for several of these cases are shown in Figs. 5-6a–d and 5-7a–d. These were all cases covering the 1996 season for the dates 20 July, 22 July, 6 August, and 29 August. During those dates active synoptic disturbances were present over India and the central Pacific Ocean as well. Figure 5-6
covers the results of box energetics for these aforementioned cases for the Indian region, and Fig. 5-7 shows the results for tropical depressions over central Pacific region. The horizontal size of these disturbances is around 3000 km, so a box was selected around these disturbances with a comparable lateral and meridional scale. The generation and energy conversion term for each case were computed and are illustrated in these panels. Boundary flux terms were not computed, so these results only confirm the internal processes. The following results stand out in all cases: There is a substantial generation of eddy available potential energy from convective heating. There is significant conversion of eddy available potential energy into eddy kinetic energy (baroclinic process) and there is a significant contribution from the local Hadley cell (i.e., energy exchange from the zonal available potential energy to zonal kinetic energy over this local domain). These salient features of the energetics are seen for the Pacific and the Indian monsoon disturbances. These results are consistent with the linear analysis of Moorthi and Arakawa (1985). The organization of convection contributes to the organization of the contributions for the covariances of convective heating and temperature and of the vertical velocity and temperature. These individual cloud elements whose horizontal scales are on the order of a few kilometers provide eddy kinetic energy for their maintenance by organizing around the scale of these disturbances.

The calculations of energy exchanges and generation and dissipation are formulated essentially following Lorenz (1967).

1) We define the principal energy quantities as follows (refer to the appendix for a list of symbols):

$$P = \frac{c_p}{2} \int_{m} \gamma_d \frac{[T]'^2}{T} dm,$$  \hspace{1cm} (5-1)

where $dm = -\frac{1}{g} dx dy dp$;

$$P' = \frac{c_p}{2} \int_{m} \gamma_d \left\{ \frac{T'^2 - [T]'^2}{T} \right\} dm;$$ \hspace{1cm} (5-2)

$$K = \frac{1}{2} \int_{m} \left\{ (u)^2 + (v)^2 \right\} dm; \hspace{1cm} \text{and} \hspace{1cm} (5-3)$$

$$K' = \frac{1}{2} \int_{m} \left\{ (u - [u])^2 + (v - [v])^2 \right\} dm,$$ \hspace{1cm} (5-4)

where $P$, $P'$, $K$, and $K'$ are, respectively, the zonal available potential energy, eddy available potential energy, zonal kinetic energy, and eddy kinetic energy over a closed domain of mass $m$. The $[\cdot]$ indicate a zonal average.

2) The principal energy transformation functions are the following with the angled brackets $\langle \cdot \rangle$ indicating an energy exchange between the quantities contained therein:

$$\langle [P] \cdot P' \rangle = -R \int_{m} \left\{ \frac{\theta}{\gamma} \right\} \left\{ \left[ T' \cdot \frac{\partial}{\partial y} \left[ T' \right] \right] \right\} \left\{ \frac{\gamma_d}{\gamma} \frac{[T]'^2}{T} \right\} dm,$$ \hspace{1cm} (5-5)

$$\langle [P] \cdot K' \rangle = -R \int_{m} \left\{ \frac{[T]'^2}{T} \right\} \left\{ \frac{\theta}{\gamma} \right\} dm,$$ \hspace{1cm} (5-6)

$$\langle [K] \cdot K' \rangle = -R \int_{m} \left\{ \left[ u' \cdot v' \right] \frac{\partial}{\partial y} [u] + \left[ u' \cdot \frac{\partial}{\partial p} [u] \right] \right\} \left\{ \frac{\gamma_d}{\gamma} \frac{[T]'^2}{T} \right\} dm,$$ \hspace{1cm} (5-7)

$$\langle [P'] \cdot K' \rangle = -R \int_{m} \left\{ \frac{\omega'}{p} \right\} \left\{ \frac{\partial}{\partial y} [u] \right\} dm.$$ \hspace{1cm} (5-8)

3) The generation of available potential energy is expressed by the relations

$$G_i = \int_{m} \left\{ \frac{\gamma_d}{\gamma} \frac{1}{T} [T']^2 [H_i]' \right\} dm \hspace{1cm} \text{and} \hspace{1cm} (5-9)$$

$$G'_i = \int_{m} \left\{ \frac{\gamma_d}{\gamma} \frac{1}{T} [T' H_i]' \right\} dm,$$ \hspace{1cm} (5-10)

where $G_i$ and $G'_i$ are, respectively, the generation terms for the zonal and the eddy available potential energy. The subscript $i$ denotes the generation for a particular heating function $H_i$. In the following analysis we shall speak of four types of heating functions and their respective contributions to the generation of available potential energy. These heating functions are shown below:

$H_R$ = radiative warming,

$H_{ST}$ = stable heating (i.e., large-scale condensation),

$H_{CON}$ = convective heating (parameterized form), and

$H_{SEN}$ = sensible heat flux from ocean and land surfaces.

4) The dissipation of kinetic energy is given by the following expressions:

$$\mathcal{D} = \int_{m} [T] \cdot [H] dm \hspace{1cm} \text{and} \hspace{1cm} (5-11)$$
where $D$ and $D'$ denote the dissipation of zonal and eddy kinetic energy, respectively, $[F]$ and $F'$ are the corresponding frictional forces per unit mass of air, and the formulation of the function $F$ should be consistent with the momentum equations of the dynamical model in use. The formulation is same as that used in Krishnamurti (1979).

4. Scale interactions: Energy exchange from synoptic to MJO time scales

The scale interactions of the synoptic time scales (3–7 days) with the MJO time scale (20–60 days) can be addressed using energy exchanges in the frequency domain following Sheng and Hayashi (1990a, b) or from the formulations of latent heat fluxes from the boundary layer to the cloud layers (Krishnamurti et al. 2003). Both of these studies convey the same essential message on these scale interactions for the maintenance of the MJO time scale. Here we shall first provide an interpretation of the scale interactions in the frequency domain from the latent heat perspective. Figure 5-8 shows some interesting aspects of the latent heat flux. Triple product nonlinearities exist in the current formulations of the surface similarity theory [i.e. the product of 1) a space–time varying exchange coefficient that is stability dependent, 2) the difference between the surface saturation specific humidity and the 10-m level specific humidity of air, and 3) the wind speed]. Triple product nonlinearity also exists in most formulations of diffusive fluxes of moisture (Manobianco 1988); in the planetary boundary layer [those carry products of the vertical wind shear and bulk Richardson number (stability and the inverse of wind shear)]. The Fourier-transformed moisture conservation equation carries these triple product terms. This expression tells us the gain or loss of moisture for a particular time scale from this triple product term. This formulation is revealing for the explicit scale interactions among different frequencies of the flow regimes. These mathematical details are provided in Krishnamurti et al. (2003). Using daily reanalysis datasets (ERA-40 from the

![Figure 5-6: Box energetics, following Lorenz (1967), showing some salient energy conversions and generation components (° s⁻¹). These figures pertain to the synoptic-scale disturbances for (a) 20 Jul, (b) 21 Jul, (c) 8 Aug, and (d) 28 Aug 1996 over the Indian region (7°–35°N, 60°–100°E); the symbols are explained in the table of acronyms and the text provides an explanation.](image-url)
ECMWF) the interactions among many time scales that interacted with the MJO time scale were computed. Here the results are shown for a period covering the boreal summer season for the year 1996. This was a period with an active MJO especially over the Pacific Ocean and the Asian monsoon belt. The salient interactions (those triads that contribute to 50% or more of the total fluxes) that called for a gain of moisture on the MJO time scale arose from the interactions of the synoptic time scales (pair of frequencies) and the MJO time scale. The trigonometric selection rules for scale interactions on the frequency domain are satisfied by many pairs of synoptic time scales and the MJO time scale; an example of such is the possible interaction of the 5- and 6-day time scale with the 30-day time scale, which satisfies the rule \( p = n - m \), where \( p = 1/30 \), \( n = 1/5 \), and \( m = 1/6 \). Of this type, there are many permissible combinations of the synoptic time scales that convey moisture to the MJO time scale. The table of numbers in Fig. 5-8d lists triplicates of numbers; those are prominent triad time scales that contributed the most toward the exchange of latent heat energy from the synoptic time scales to the MJO time scale. Figures 5-8e–h illustrate the corresponding fluxes (similar to Figs. 5-8a–d, respectively) for the fluxes in the planetary boundary layer. These values of fluxes are larger for all the respective illustrations. Here again the important message is that the total moisture fluxes by the salient triads are quite significant when compared to Fig. 5-8e, which carries the total fluxes on the MJO time scale.

Figure 5-9 shows a similar illustration for the tropical western Pacific Ocean that conveys essentially the same inference as above for the Indian Ocean. The important message that is conveyed by these computations is that the vertical flux of moisture on the time scale of the MJO largely comes from selective triads that invoke scale interactions of the MJO time scale with a pair of synoptic-scale disturbances. That feature is seen largely over the...
FIG. 5-8. Latent heat fluxes (W m\(^{-2}\)) over the Indian Ocean region. (a) Total latent heat fluxes on the time scale of the MJO across the constant flux layer. (b) Total fluxes of latent heat across the constant flux layer on the time scale of the MJO arising from interaction of the MJO with the synoptic time scale of 2 to 7 days. (c) Fluxes of latent heat contributed by salient (strongest contributing) triad interactions in the surface layer. (d) Salient triad interaction frequencies contributing to latent heat fluxes on the time scale of the MJO across the constant-flux layer. (e) Total latent heat fluxes on the time scale of the MJO in the planetary boundary layer (PBL) at 850 hPa. (f) Total latent heat fluxes in the PBL on the time scale of the MJO arising from interaction of the MJO time scale with the synoptic time scale of 2 to 7 days. (g) Latent heat fluxes contributed by the salient triad interactions in the PBL. (h) Salient triad interaction frequencies contributing to latent heat fluxes on the time scale of the MJO in the PBL at 850 hPa [adapted from Krishnamurti et al. (2003)].
tropical Indian Ocean and the tropical western Pacific. We had carried out these same computations over the rest of the tropics and did not see a large contribution to such interactions of the synoptic scales with the MJO time scale.

The findings of Sheng (1986) and Sheng and Hayashi (1990a,b) addressed this problem in the frequency domain. Hayashi (1980) laid the formulation for the energy exchanges in the frequency domain. Basically this
approach follows the energetics in the wavenumber domain (Saltzman 1970). Hayashi (1980) decomposed the meteorological time series into its Fourier components in such a way that energy exchanges can be viewed through several spectral windows in the time domain. Sheng and Hayashi (1990a,b) utilized 365 days (the fundamental mode of their frequency domain) of the FGGE year dataset in their study. In the context of the MJO time scale one of their main conclusions was the energy exchanges from fast transient motions (the tropical synoptic scales to the slow transients on time scales of a month). Their study provides an important summary on the scale interactions pertinent to the synoptic scales (identified as fast transients) and the MJO time (identified as slow transients). The fast transients are a major source of energy for the slow transients. That is a kinetic to kinetic energy exchange that largely arises from the triad interactions among synoptic and the MJO time scale; generally, two members of the synoptic time scales interact with a member of the MJO time scale to bring about this exchange following the triad selection rules. Somewhat surprisingly, this study also brings to light the possibility of baroclinic energy exchange (warm air rising and relatively colder air sinking) as a source of energy for the slow transients (the MJO time scale) from the available potential energy of the slow transients. This latter feature was not confirmed in our more recent findings. There is, however, agreement on the findings that those nonlinear advective processes that lead to the triad energy exchange terms in the energy equation are robust contributors to the maintenance of the MJO time scale.

In this study we shall further illustrate the energy exchanges from the synoptic scales to the MJO time scale following Krishnamurti et al. (2003). This also draws upon triad interactions of the latent heat fluxes of the boundary layer physics.

Sheng and Hayashi (1990b) consider three time scales, the long-term mean, which is the mean of the mean state of the 365 days and is the fundamental mode, and the annual cycle of the fast and the slow transients. Both the available potential energy and the kinetic energy exchanges in the frequency domain were calculated by them (Fig. 5-10). These results confirm the findings of the present study.

We shall not be reiterating the energy exchange equations again here, since they have appeared in Sheng and Hayashi [1990a,b; see Eqs. (9)–(12)].

The year 1996 was a robust MJO wave activity (Fig. 5-11). The eastward-moving divergent wave is best seen from the velocity potential datasets at the 200-hPa level (Krishnamurti 1971); the velocity potential on the time scale of the MJO (20–60 days) is shown here. Figure 5-11 presents alternating passages of positive and negative velocity potential anomalies shown by solid and dashed lines, respectively, on this time scale, which traverse from west to east. Superimposed on these velocity
potential isopleths are the total outgoing longwave radiation (OLR) fields. These are all averages for the equatorial latitude belt 10°S to 10°N. This illustration does not clearly show a global relationship between the MJO and OLR (a proxy for cloud cover). For this reason, the relationship of the divergent motions and OLR was next examined over several longitudinal sectors. In Fig. 5-12 we show time series (along the abscissa) of the velocity potential and OLR over the following longitudinal belts: Africa, the Indian Ocean, western Pacific, central and eastern Pacific, and equatorial Atlantic. The correlation among these two pairs of curves is inserted. This suggests a poor relationship between OLR and the MJO waves over Africa, central and eastern Pacific, and the tropical Atlantic, implying that the relationship is stronger over the western Pacific and Indian Ocean sectors. Our study suggests that latter two regions are the most important for the scale interactions among the synoptic-scale motions (with organized convection driving the synoptic scale) and the MJO time scale via the dynamical triads. This display suggests that the MJO is not directly connected to the tropical clouds at all longitudes.

5. Conclusions

The atmospheric Kelvin wave is clearly a starting explanation for a slow eastward-moving wave with its largest amplitude residing in the equatorial latitudes. The earlier renditions of this wave come from the classical linearized shallow water equations studies that were illustrated by Matsuno (1966) and many others. Lau and Peng (1987) showed that this equatorial Kelvin wave in the absence of organized convection moves too fast at almost twice the eastward speed of the MJO wave. Using a multilevel atmospheric AGCM they showed a slowing down of the Kelvin wave by invoking wave CISK for the cumulus parameterization following Lindzen’s (1974) original framework of wave CISK. That formulation essentially assumes that rising motions (on top of the boundary layer) exist along an entire active half of an MJO wave. This is equivalent to stating that MJO is quite like a hurricane and is driven by deep convection directly along its entire scale. The MJO being a planetary wave, this called for an organization of convection following the MJO along the entire active half of the MJO wave around Earth.
The wording “organization of convection and of dynamics” is somewhat synonymous with scale interactions that invoke quadratic and triple product nonlinearities. The trigonometric selection rules for quadratic and triple product nonlinearities in the energy equation are closely tied to the issue of organization of convection and of dynamics respectively. If deep convection is organized around a disturbance, then the generation of eddy available potential energy, the conversion of eddy available potential energy into eddy kinetic energy, and the maintenance of kinetic energy of the disturbance all get organized around the same frequency of that disturbance.

FIG. 5-12. Variability of filtered velocity potential (light lines) and unfiltered OLR anomaly (dark lines) for summer season of year 1996: (a) Africa region (10°S–10°N, 0°–50°E), (b) Indian region (10°S–10°N, 50°–90°E), (c) western Pacific region (10°S–10°N, 90°–140°E), (d) central Pacific region (10°S–10°N, 140°E–220°W), (e) eastern Pacific region (10°S–10°N, 220°–280°W), and (f) Atlantic region (10°S–10°N, 280°–340°W).
the frequencies of that disturbance are denoted by \(n\), then the selection rule for quadratic nonlinearity simply states that each member of \(n\) can only interact with the component frequency of \(n\), all other interactions being identically equal to zero. We have addressed the energy exchanges among the synoptic scales and the MJO time scale using results from two different studies. One of these follows the approach of Hayashi (1980), which focuses on energy exchange in the frequency domain, and the other is on the latent heat fluxes of the planetary boundary layer physics (Krishnamurti et al. 2003). Both approaches invoke triple product nonlinearities and call for exchanges of energy from the synoptic scales to the MJO time scales toward the maintenance of the latter. Both of these approaches carry triads where two time scales of the synoptic scales interact with a time scale of the MJO time scale and provide energy to the latter. These transfers are facilitated by the triple product selection rules and hence we can label these as organization of dynamics.

In this paper we have shown, from formal computations of Lorenz box energetics, that during periods of presence of an active MJO, robust tropical synoptic disturbances of the central and western Pacific and the Indian monsoon environment carry organized convection that generate eddy available potential energy and a transformation of eddy available potential energy to the eddy kinetic energy on the scales of such disturbances. The maintenance of the eddy kinetic energy of such disturbances is largely attributed to convective processes for the generation of the eddy available potential energy and baroclinic processes for the transformation of the eddy available to the eddy kinetic energy.

A major scientific issue that has come up in the design of field experiments such as the DYNAMO is whether clouds organize on the space time scale of the MJO and directly drive the MJO in the same manner as organized convection drives synoptic tropical disturbances. Organized convection on the MJO time scale is seldom seen over the tropical eastern Pacific and the tropical Atlantic. The MJO wave spatially covers the global tropics as a planetary wave (Madden and Julian 1971). Furthermore, taking one complete cycle of an MJO (20–60 days), even over the western tropical Pacific and the Asian monsoon belt we seldom see convection organized on the scale of the MJO for an entire cycle. However, whenever active synoptic scales are present we do often see well-organized convection on the scale of such disturbances. Our contention is that convection is only organized on the scale of synoptic (and meso-scale) disturbances and not on the space–time scales of the MJO. The mode of communication of the synoptic scales with the MJO is via nonlinear dynamics. This also brings up the issue of “Who modulates whom?” Nearly all the literature alludes to the modulation of tropical weather during the passage of an MJO wave. That has been verified over the tropical western Pacific and the Asian monsoon belt including northern Australia during the boreal winter season. Careful examination of weather maps over these regions always shows that tropical weather as a part of a tropical mesoscale or a synoptic-scale system. The MJO wave is very weakly divergent and carries typical magnitudes of convergence and divergence on the order of \(10^{-7}\) to \(10^{-6}\) s\(^{-1}\). That appears to be necessary to initiate weak moistening and the start of convection; however, it is the simultaneous passage of a mesoscale or a synoptic-scale disturbance, in that region, that exploits this weak modulation of weather from the passage of the MJO wave. It is the organized convection in a mesoscale and synoptic-scale disturbance that contributes to the maintenance of the mesoscale and synoptic scale. The MJO is maintained by the synoptic scales via nonlinear energy transfers.

**APPENDIX**

**Definition of Variables**

Table 5-A1 lists the variables with their definitions.

**REFERENCES**


