Intraseasonal Variability in Tropical Mean Temperature and Precipitation and Their Relation to the Tropical 40–50 Day Oscillation

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ABSTRACT

Intraseasonal variability of tropical mean tropospheric temperature and precipitation are investigated using newly available gridded datasets from the satellite-based microwave sounding unit (MSU). Lag regression and cross-spectrum analysis reveal a strong, dynamically consistent, zonally symmetric component of the tropical 40–50 day oscillation. A fast eastward propagating signal is found in upper-tropospheric temperature and zonal wind, emanating from the region of enhanced precipitation associated with the 40–50 day oscillation. The temperature signal is consistent with an interpretation in terms of the transient tropospheric response to the switch-on of an equatorial heat source, in the form of a Kelvin wave front, and a recently detected very fast (≈40 m s⁻¹) tropical tropospheric signal, with a vertical structure suggestive of the first baroclinic mode. Such fast moving wave fronts are hypothesized to be instrumental in maintaining the observed high degree of homogeneity in tropical temperature fields by effectively redistributing the warming generated by latent heat released in regional convective systems over the entire Tropics.

1. Introduction

The intraseasonal variability of the tropical atmosphere has been the focus of many research papers since a planetary-scale oscillation with 40–50 day period was discovered by Madden and Julian (1971, 1972) in zonal wind and surface pressure data at equatorial stations. The present work is concerned with the variability of tropical tropospheric mean quantities on intraseasonal timescales and its link to this 40–50 day or Madden–Julian oscillation (MJO hereafter).

There now exist a large number of observational studies describing the spatial and temporal behavior of the MJO (see Madden and Julian 1994 for a review). Hendon and Salby (1994), using gridded fields of satellite-derived temperature estimates, gave a detailed picture of the relationships between different dynamical variables. These studies portray the MJO as an eastward propagating zonal circulation cell, with zonal winds of opposite sign in the upper and lower troposphere. The signal in the equatorial zonal wind is present throughout the entire tropical belt in the upper troposphere, whereas it is confined to the Indian and western Pacific Oceans in the lower troposphere (Madden and Julian 1972). The rising branch of the circulation cell is associated with a region of enhanced convection, which develops over the Indian Ocean, intensifies, and propagates into the western Pacific at a speed of about 5 m s⁻¹. The subsequent evolution of the region of enhanced precipitation varies from event to event and, in general, the rate of eastward propagation is less uniform (Weickmann et al. 1985). The development of anomalous precipitation also depends on the season, particularly in the Pacific region (e.g., Weickmann et al. 1992).

The precipitation anomaly decays as it reaches the region of colder surface waters around the date line. The circulation anomalies associated with the MJO have been classified into two regimes: a convective regime across the eastern Indian and western Pacific Ocean, and a dry regime elsewhere (Gutzler and Madden 1989). In the convective regime, the circulation anomalies consists of a coupled Kelvin–Rossby wave-like response (Gill 1980), which migrates eastward with the precipitation anomaly at ≈5 m s⁻¹. As the precipitation anomaly dies out over the central Pacific Ocean, the circulation anomaly assumes the form of a fast, eastward propagating signal confined to the upper-tropospheric zonal wind. Estimates of its rate of eastward propagation in this ‘dry regime’ range from 10 to 15 m s⁻¹ (Knutson et al. 1986; Hendon and Salby 1994). In the upper troposphere the region of enhanced precipitation is also accompanied by subtropical cyclones to the east and anticyclones to the west (Weickmann et al. 1985). The time interval between two such precipitation events usually ranges from 30 to 60 days (Madden 1986).

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Variations in surface pressure associated with the MJO show very fast eastward propagation (\(\sim 40\) m s\(^{-1}\)) over the eastern Pacific and exhibit a zonal mean component (Madden and Julian 1972, 1994). A zonal mean component of the MJO is also evident in the intraseasonal variability of global atmospheric angular momentum (GAM) (see Rosen 1993 for a review). Only recently has the association of GAM variations with the MJO spawned interest in the zonal mean component of the MJO (e.g., Hendon 1995).

Most of the previous work on the MJO has been focused on the wavy or zonally asymmetric part of the tropospheric fields, with a view toward explaining its existence and the physical processes that determine its characteristics. Zonal propagation has mostly been discussed implicitly in terms of the phase speed of zonal wavenumbers. In this context, the zonal mean (wavenumber 0), of course, does not contain any propagation information. For a confined, expanding anomaly with nonzero, increasing zonal mean, however, the exclusion of the zonal mean might lead to gross underestimates of its rate of propagation. This rate is defined here as the velocity at which the front of the anomaly propagates—that is, the speed at which a signal emanates from a source region.

The present study emphasizes the intraseasonal variability of tropical mean quantities, which is largely a reflection of the zonally symmetric component of the MJO. It considers the linkages between regional phenomena and the phenomena extending over the entire tropical belt. Rate of propagation throughout the paper refers to a signal velocity as just discussed, rather than the phase speed of the wave components of the oscillation. Use is made of satellite-derived datasets of oceanic precipitation and tropospheric temperature, similar to the temperature data used by Hendon and Salby (1994).

The data and the analysis method are described in section 2. Regression maps of the temperature, precipitation, and wind fields are presented and discussed in section 3. In section 4 cross-spectrum analysis is performed among tropical mean time series and between time series that have been used in previous studies of tropical intraseasonal variability. A discussion of the results is presented in section 5.

2. Data

Gridded temperature and precipitation fields are derived from radiances measured by the microwave sounder unit (MSU) that has been carried aboard the National Oceanic and Atmospheric Administration (NOAA) TIROS-N series of satellites since 1979. The data were obtained from the NASA/ Marshall Space Flight Center. This study makes use of MSU-derived lower-tropospheric (surface--300 mb) temperature, upper-tropospheric (500--100 mb) temperature, and oceanic precipitation for the period 1979--93. Lower-tropospheric temperature is based on a linear combination of MSU channels 2 and 3 (hereafter denoted as MSU23) and upper-tropospheric temperature is based on a linear combination of channels 3 and 4 (hereafter denoted as MSU34). The oceanic precipitation estimates are derived from an algorithm involving data from channels 1, 2, and 3. For technical details on MSU temperature retrievals see Spencer et al. (1990) and on MSU precipitation estimates see Spencer (1993). In addition to the MSU data, daily European Centre for Medium-Range Weather Forecasts (ECMWF) wind analysis for 1986--1993 at the 1000, 850, and 200 mb levels are used.

Pentad mean fields were constructed by averaging the available data in five consecutive daily fields, starting with 1 through 5 January 1979. A grid point in the pentad mean field is set to missing when data were available for less than 3 of the 5 days. Tropical mean time series were constructed for the MSU data by taking the average of the available pentad mean data in the latitude band 20°S to 20°N. Visual inspection of these time series, a 1-yr sample of which is shown in Fig. 1, gives the impression that the intraseasonal variability of tropical mean temperature is quite pronounced, with amplitudes ranging up to \(-0.5\) K during this particular period. It can also be seen that peaks in the precipitation time series are in fairly good alignment with maxima in the temperature time series.

Despite the fact that there exist pronounced seasonal variations in the behavior of anomalies associated with the MJO (Madden 1986; Weickmann et al. 1992), a seasonally stratified analysis does not alter the qualitative results of this study. We feel that the benefits of using a larger sample outweigh the errors incurred in averaging over seasonally varying phenomena.

Figure 2 shows power spectral densities of the MSU time series, along with the spectra of time series used as reference time series for regression analysis in several previous studies of tropical intraseasonal variability. A filtered version of outgoing longwave radiation at the equator and 85°E (OLR85E) has been used by Hendon and Salby (1994), and global angular momentum (GAM) has been used by Kang and Lau (1994). The GAM pentad time series, obtained from Dr. Kang, is defined as having 72 pentads yr\(^{-1}\) for the period 1980--89; that is, some of those pentad means are, in fact, 6-day means. We modified this time series by inserting extra pentads into it, to make it have the same number of points for the period 1980--89 as our time series. The central time associated with each pentad in the modified GAM time series differs by no more than 2.5 days from that of the associated pentads in our time series. This adjustment results only in a small difference between the original and modified GAM time series, when each is plotted on its respective time axis. Also shown is the spectrum of an index of the zonal mean equatorward surface flow (referred to here as the
meridional convergence index), which is included here because of the close relation of the zonally averaged meridional circulation to the other zonal mean quantities, which will become apparent in subsequent sections. The meridional convergence index is constructed from the meridional component of the 1000-mb ECMWF wind field by subtracting the mean for the 10°–20°N belt from the mean of the 10°–20°S belt.

The spectra are constructed by Fourier transforming the unsmoothed autocorrelation function using a maximum lag of 36 pentads, which yields spectral estimates for 36 frequency bands with a bandwidth of (365

FIG. 1. Pentad-mean time series of the mean over the tropical belt from 20°S to 20°N of MSU34 (upper curve), MSU23 (middle curve) temperatures, and MSU precipitation (lower curve) for 1979. Units are kelvin and millimeters per day for the MSU temperatures and precipitation, respectively. Intraseasonal peaks of the precipitation are indicated by dashed lines.

FIG. 2. Normalized power spectra of the reference pentad mean time series, based on data from 1979–93 for the MSU and OLR85E data, from 1980–89 for GAM, and from 1986–93 for the meridional convergence index. The abscissa is frequency in cycles day$^{-1}$ and the 30–60 day band is bracketed by the dashed lines.
days)\(^{-1}\). Coherences presented in section 4 are obtained by Fourier transforming the cross-correlation function with the same number of lags, where the complex cross spectrum is averaged over the estimates for the six frequency bands corresponding to periods ranging from \(\sim 32\) to \(\sim 66\) days. Due to the differing periods of record of the various time series, the absolute value of the 99.9% significance levels for squared coherence ranges from 0.07 for the pairs of time series with 15 years of data concurrently available, to 0.25 for those with only 4 years available.

The variance of the time series, shown in Fig. 2, is dominated by the annual cycle and longer timescales. The OLR85E and precipitation time series exhibit substantial variability in the intraseasonal period (30–60 day) band. The point of showing these spectra is not to prove the existence of periodicities or the significance of spectral peaks, but merely to give background information on the time series, supplementing Fig. 1.

Linear regression analysis is a simple method of documenting the spatial patterns associated with fluctuations in a reference time series. To obtain patterns associated with intraseasonal fluctuations in the tropical mean of tropospheric temperature or precipitation, filtered reference time series are created by subtracting a 19-point (i.e., 95 day) running mean from each of the MSU pentad time series. This procedure, in combination with the use of pentad means, effectively retains fluctuations on timescales from 10 to 100 days. For the purpose of regression analysis it is sufficient to just filter one of the time series involved, saving us the work of having to filter the map time series. Therefore, the raw pentad fields are regressed onto these filtered reference time series.

3. Regression analysis

Figure 3 shows the lag regression maps of MSU34 and 200-mb winds (a) and MSU23 and 850-mb winds (b) onto tropical mean precipitation for lag intervals ranging from a 15-day lead to a 5-day lag of the mapped variable. Regions of strong positive (negative) precipitation anomalies associated with variations of the tropical mean precipitation are indicated by dark (light) shading in both (a) and (b).

A positive precipitation anomaly develops in the Indian Ocean from lag \(-5\) days to \(-10\) days, then grows and spreads eastward across the maritime continent into the western Pacific by lag \(-5\) days. At zero lag the region of anomalous precipitation extends over most of the western Pacific from 20°S to 20°N and extends along the Pacific ITCZ almost to the American coast, with a small anomaly affecting the Atlantic ITCZ as well. Over the Indian Ocean the anomaly weakens from lag \(-5\) days to 0 days and splits into bands along 10°S and 10°N. When the data are stratified by season (not shown) the precipitation is concentrated in the summer hemisphere band. By lag \(+5\) days the precipitation anomaly has begun to dissipate, particularly over the Indian Ocean and the far western Pacific.

In the upper troposphere (Fig. 3a) the eastward propagating precipitation anomaly is accompanied by a warming of the whole Tropics by 0.15 K from lag \(-15\) days to \(+5\) days. It is likely that during intervals when the oscillation is present with large amplitude, as in June–October 1979 (Fig. 1), the warming would be substantially larger. Superimposed on this general warming is a structure reminiscent of the linear response to equatorial heating (Gill 1980), with a warm tongue protruding eastward along the equator out of the region of anomalous precipitation, and subtropical warm cells to the west of the precipitation on both sides of the equator. This configuration propagates eastward with the enhanced precipitation from lag \(-10\) days to lag zero, with the maximum temperatures on the equator lying slightly to the east of the enhanced precipitation. The evolution of the warming is characterized by a rapid expansion of the warm tongue toward the east, consistent with the transient atmospheric response to a switched on heat source (Heckley and Gill 1984). A subsequent meridional broadening of the warm region is evident from the southward migration of the zero contour in the western hemisphere from lag \(-5\) days to \(+5\) days. The eastward propagation of the subtropical warm cells can be seen more clearly in the Southern Hemisphere, where the center of the cell moves from the eastern Indian Ocean to Australia.

The temperature anomalies should be approximately proportional to the upper-tropospheric geopotential height anomalies. Hence the anomalous winds in Fig. 3a are dynamically consistent with the temperature anomaly fields, with downgradient flow along the equator and anticyclonic flow around the subtropical warm cells.

The westerly outflow from the region of precipitation, which develops from lag \(-5\) days to \(+5\) days, wraps around the tropical belt to the Indian Ocean. In the Heckley and Gill model the transient response to the east of a switched on heat source is characterized by a fast Kelvin wave front, in which equatorial warm anomalies are accompanied by anomalous westerlies and both propagate at the same speed. Estimating the eastward rate of propagation of the upper-level wind signal in Fig. 3a by observing the movement of the eastern front of the equatorial zonal outflow between lag \(-5\) days to \(+5\) days from \(\sim 105°W\) to \(\sim 45°E\), yields a propagation rate of \(\sim 15°/\text{day} \approx \sim 20\) m s\(^{-1}\). This rate is in agreement with the results of cross-spectrum analysis between Canton surface pressure and upper-tropospheric zonal wind at selected tropical stations by Madden and Julian (1972). It is not in agreement, however, with the propagation speed of the temperature signal, which is much faster. The flow anomalies in Fig. 3a, therefore, cannot be associated with the Heckley and Gill type Kelvin wave front. The wind anomalies associated with the temperature signal seen in Fig. 3a...
Fig. 3. Lag regression maps of (a) MSU34 temperature (contours), 200-mb winds (vectors), and MSU precipitation (shading); and (b) MSU23 temperature (contours), 850-mb winds (vectors), and MSU precipitation (shading) onto bandpass-filtered tropical mean MSU precipitation. The magnitude of the fields is scaled to represent the anomalies associated with a positive anomaly in tropical mean MSU precipitation of one standard deviation. Contour interval 0.05 K; the zero contour is thickened and negative contours are dashed; vectors >1 m s$^{-1}$ and >0.4 m s$^{-1}$ are shown for the 200-mb and 850-mb levels, respectively; positive (negative) precipitation anomalies exceeding 0.6 mm day$^{-1}$ are indicated by dark (light) shading. The sequence of maps represents anomalies from 15 days prior to (top panel) to 5 days after (bottom panel) a maximum in tropical mean MSU precipitation. The contoured fields are cosmically smoothed by eliminating features with zonal wavenumbers >6.
are probably small enough to be masked by larger wind variations related to the MJO.

Anomalies in the precipitation and upper-tropospheric temperature fields are decreasing and dissipating beyond +5 days lag, with the upper-level equatorial westerlies remaining strong until lag +10 days (not shown). In the sequence of maps, the anomaly equatorial zonal flow evolves from predominantly easterlies at lag −15 days to predominantly westerlies at lag +5 days, reflecting the relation between MJO and GAM variations.

Figure 3b shows the anomalies in temperature and winds in the lower troposphere associated with tropical mean precipitation. As in the upper troposphere, the
lower troposphere over the whole Tropics warms up while the precipitation intensifies from lag -15 days to lag zero. The warming at this level, however, exhibits a much stronger zonally asymmetric component; the equatorial central Pacific region warms up by 0.25 K, while the equatorial Indian Ocean region barely warms at all (0.05 K). Again, a warm tongue to the east of the precipitation and warm cells to the west, with centers around 20°-25° latitude in both hemispheres, can be seen. In addition, there are subtropical cold cells over the Pacific that propagate eastward slowly ahead of the precipitation. A qualitatively similar spatial structure was shown by Jin and Hoskins (1995) to be the response of a 15-level primitive equation model to equatorial heating.

In general, the response in the lower troposphere seems to be more regional in character, being largely restricted to the Pacific Ocean, whereas the upper-tropospheric response is best characterized as being of planetary scale. The anomalous 850-mb winds over the Pacific basin at lags -5 days and 0 days are in the opposite direction to those at 200 mb, which supports the notion of a simple baroclinic structure of the atmospheric response to the convective heating in this region. Zonal outflow from the region of enhanced precipitation at the 200-mb level is accompanied by zonal inflow at the 850-mb level.

The corresponding series of lag regression maps of the 1000-mb wind field onto the tropical mean precipitation time series is shown in Fig. 4 for lags -10 days to 0 days. At lag -10 days, a strengthening of the trade-wind circulation can be seen over the central Pacific Ocean in both hemispheres. When the precipitation anomaly is established over the western Pacific Ocean by lag -5 days, the surface flow anomalies extend to the equator over the central Pacific Ocean and are now more zonally oriented in the Southern Hemisphere. At this time surface flow anomalies are also seen over the Indian and Atlantic Oceans, which strengthen as the precipitation anomaly reaches its peak at zero lag.

Part of the 1000-mb flow anomalies can be interpreted as zonal inflow into the region of enhanced precipitation. In contrast to the 850-mb flow anomalies, significant meridional convergence is apparent over the
Pacific Ocean and the southern parts of the Indian and Atlantic Oceans, indicating an enhancement of the mean meridional circulation into the equatorial belt. Over the western Indian Ocean, a summer monsoon-like cross-equatorial circulation can be seen to develop from lag −5 days to zero lag, which is present in a weaker form in the 850-mb flow as well. Seasonally stratified analysis shows that this feature is indeed present only during northern summer.

In summary, the regression maps based on the tropical mean precipitation resemble the composite life cycle of an MJO event, presented by Knutson and Weickmann (1987), and Hendon and Salby (1994). In addition, there emerges a dynamically consistent picture in the zonal mean quantities. The zonally averaged equatorward surface flow is consistent with the associated precipitation changes, the latent heating associated with the enhanced precipitation is consistent with the warming of the troposphere, and a warmer equatorial troposphere is consistent with stronger upper-level westerlies.\(^1\) It should be stressed here that the temperature—zonal flow relation is of pure diagnostic nature and does not imply a causal relationship. Zonal mean acceleration requires momentum flux convergence, likely to result from the heating induced anomalous circulations being superimposed on a zonally asymmetric basic flow (Weickmann et al. 1996, manuscript submitted to J. Atmos. Sci.; Hoskins 1995, personal communication).

The corresponding regression maps based on MSU temperature are quite similar, but the MSU precipitation time series exhibits a slightly stronger coherence with the other zonal mean variables, as will be shown in the next section.

Figure 5 shows a compressed representation of the series of regression maps just described, in the form of a lag/longitude section. This form of presentation is particularly well suited for displaying the zonal propagation along the equator. Shown are the mean anomalies in the belt extending from 5°S to 5°N and the display is repeated once in longitude for convenient observation of signals propagating around the globe.

In the upper troposphere (Fig. 5a) the dominant feature is the almost simultaneous warming and cooling of the entire equatorial belt, preceded by enhanced precipitation between 90°E and the date line. The precipitation anomaly propagates eastward by about 60° of longitude over a 10-day interval, which is equivalent to a speed of \(\sim 8\) m s\(^{-1}\). Closer inspection of the warming period (lag −10 days to +5 days) reveals that the warming does not take place absolutely simultaneously over the entire equatorial region, but can be viewed as a signal, rapidly emanating eastward from the region of enhanced precipitation. An estimate of its propagation speed obtained by fitting a straight line to the temperature contours and estimating the slope in degrees of longitude per day, yields \(\sim 40\) m s\(^{-1}\), which is in close agreement with recent results from Milly and Madden (1996). They found evidence of a first baroclinic mode structure, which propagates eastward at \(\sim 40\) m s\(^{-1}\) over the central and eastern Pacific. This speed also agrees with cross-spectral analysis of surface pressure data in the same region (Madden and Julian 1972, 1994). Heckley and Gill (1984) found that the response to the east of a switched on heat source, in a shallow water model, consists of a Kelvin wave front emanating from the source at \(\sim 50\) m s\(^{-1}\).

Contrast, the cooling takes place simultaneously over the whole globe, as indicated by the horizontal

\(^1\) On an equatorial \(\beta\) plane a warmer equatorial region—i.e., positive upper-level geopotential height anomalies—is in geostrophic balance with stronger equatorial upper-level westerlies, at least for natural choices of the meridional anomaly structure [e.g., cos(y), bell shape], even though there is no temperature or geopotential height gradient right on the equator.
orientation of the temperature contours beyond lag +10 days. The zonal wind anomalies again show the outflow from the region of enhanced precipitation, initially toward the west, but then predominantly toward the east, along with an eastward propagation of the westerly wind anomalies. Westerly wind anomalies prevail at the warmest longitudes and easterlies at the coldest longitudes. A pronounced westerly acceleration of the zonally averaged flow is apparent from day −10 to day +5, reflecting the tendency of the zonally symmetric flow to remain in balance with the temperature field.

The picture in the lower troposphere (Fig. 5b) is less zonally uniform. The warming starts 5 to 10 days earlier than the warming in the upper troposphere over the Indian and western Pacific Oceans and reaches the Atlantic sector almost 5 days later. Also, the signal in the 850-mb zonal wind seems to be more restricted to the vicinity of the enhanced precipitation. A region of easterlies of 60°–90° in longitudinal extent leads the region of precipitation and propagates eastward ahead of it at about the same speed. A region of westerlies of similar extent lags the precipitation and follows it, partially overlapping with it. However, it should be noted that a zonal wavenumber 1 signature is evident in the zonal wind field from lag −5 days−+5 days.

The space/time structures associated with fluctuations of the tropical mean precipitation can be summarized as follows. Intraseasonal variations in the tropical mean precipitation manifest themselves as eastward propagating anomalies in the Indian and western Pacific region, which can be associated with MJO events. The precipitation is accompanied by zonal convergence below and zonal outflow aloft, consistent with the linear response to equatorial heating (e.g., Gill 1980). A rapidly eastward propagating upper-tropospheric temperature signal emanates from the region of enhanced precipitation, leading to a warming of the troposphere over the entire tropical belt, consistent with simple modeling results by Heckley and Gill (1984). The responses of the lower and upper troposphere differ in that the lower-tropospheric features are more regional in character, tied to the slowly eastward propagating precipitation anomaly over the Indian and western Pacific Oceans. The upper-tropospheric response is characterized by a signal in temperature and westerly winds, which rapidly travels eastward around the globe, yielding an almost zonally uniform response in the temperature field.

Figure 6 is a repetition of Fig. 5 with the zonally symmetric component in the temperature and wind regressions removed. This figure demonstrates how the exclusion of the zonal mean alters the appearance of the tropospheric anomalies associated with tropical mean precipitation. Temperature anomalies in the lower and upper troposphere are remarkably similar in this figure, and the out of phase relation between 850 and 200-mb zonal winds holds over a substantially larger range of longitudes than in Fig. 5. The zonally asymmetric part of the anomalies is dominated by zonal wavenumber 1, which exhibits a uniform eastward phase propagation of ∼6 m s⁻¹ between lags −25−−5. The amplitude of the wavenumber 1 component increases as the precipitation anomaly reaches its maximum around zero lag, then its phase speed increases, as indicated by the distinct bend in the temperature contours around 170°W. This feature is also present in lag/longitude sections presented in Hendon and Salby (1994, their Fig. 6) and has been interpreted as the MJO being partitioned into a forced and freely propagating mode in the Eastern and Western Hemisphere, respectively.

4. Cross-spectrum analysis

To obtain a more detailed and objective view of the phase relationships between the various zonally averaged quantities in the time domain, cross-spectrum analysis was performed between the meridional convergence index, derived from the equatorward flow at the 1000-mb level, the time series of the MSU precipitation and temperature averaged over the tropical belt 20°S−20°N, and the time series of 200-mb zonally averaged zonal wind averaged over the 10°S−10°N belt (U200). To facilitate comparison with previous studies a time series of outgoing longwave radiation on the equator at 85°E (OLR85E) and a global angular mo-
momentum (GAM) time series were included in the cross-spectrum analysis. A filtered version of the OLR85E time series was used by Hendon and Salby (1994) as an index for the MJO, and GAM was shown to be linked to tropical wind anomalies associated with the MJO (e.g., Anderson and Rosen 1983). GAM has also been used as a reference variable for producing regression maps similar to the ones shown in this study (Kang and Lau 1994).

Figure 7 shows the amplitudes of the complex cross spectra, normalized by dividing by the covariance between the two time series, for combinations of MSU precipitation, MSU34 and MSU23 temperatures, the meridional convergence index, GAM, OLR85E, and U200. The amplitude spectra display how the covariance between the time series is distributed over the frequency range. The annual cycle dominates the covariance between all of the time series. For combinations involving MSU precipitation or OLR85E the covariance inside the 30–60 day band, bracketed by the vertical lines, tends to be higher than in neighboring bands. Table 1 shows the squared coherences and phases for the 30–60-day band indicated in Fig. 7. Most entries in this table are significantly different from zero at the 99.9% level. The fact that OLR85E is less coherent with our reference time series than any of the zonally averaged indices might seem disturbing at first sight, since a filtered version of OLR85E was the MJO index.

![Fig. 7. Normalized amplitudes of the complex cross spectra between reference time series based on data from 1979 to 1993 for combinations among MSU and OLR85E; from 1980 to 1989 for combinations of GAM with MSU or OLR85E; from 1986 to 1993 for combinations of the meridional convergence index or U200 with MSU or OLR85E; and from 1986 to 1989 for the combination of GAM with U200 or the meridional convergence index. The abscissa is frequency in cycles day\(^{-1}\) and the 30–60 day band is bracketed by the dashed lines.](image-url)
Table 1. Coherence squared (in hundreds) and phase (in hundredths of a cycle) between combinations of index time series for the frequency band corresponding to periods from 32 to 66 days as obtained from cross-spectral analysis. Coherence squares exceeding the 99.9% significance level are typed in bold face. Other coherence square entries exceed the 99% significance level. Periods of record are the same as in Fig. 6.

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used by Hendon and Salby (1994). But as can be inferred from the eastward propagating precipitation anomaly on the lag regression maps (Fig. 3), the MJO and the tropical mean precipitation are certainly related. The low coherences of OLR85E can be attributed to the fact that it is an index, representative of only one gridbox in the Indian Ocean, whereas all the other time series represent zonal averages. Furthermore, the filtering in space and the conditional sampling in time employed by Hendon and Salby (1994) improve the quality of OLR85E as an MJO index.

The fact that many of the coherence squares are less than 0.3 serves as a reminder that the MJO is not the only phenomenon that influences the variables in Table 1 in the 30–60 day period band. Nonetheless, the very high significance levels and the fact that phase relationships between various pairs of variables are consistent indicate that we can obtain reliable phase information from Table 1. Figure 8 presents this phase information in a more visual form. The figure is arranged in a circle to represent the various stages in the life cycle of one MJO event as determined from the spectral analysis, but only one-half cycle is shown in order to avoid the implication that the phenomenon is periodic. All phase information refers to the statistical mean MJO event and lags are prescribed assuming a mean time span of 50 days from one event to the next. To facilitate comparison with the regression maps associated with different phases of the MJO cycle (Figs. 3 and 4), lags are given in relation to maximum tropical mean precipitation. The phases in this figure are determined by obtaining the phase differences between neighboring variables on the circle from Table 1.

We define the start of an MJO event as coinciding with the peak of the precipitation anomaly over the Indian Ocean (OLR85E−). This phase of the cycle corresponds to the −10 panels in Fig. 3. In reality there might be large-scale processes that precede the precipitation anomaly in the Indian Ocean that are instrumental in triggering it, but that is not the concern of our study. Some 6 days later the mean meridional circulation reaches a maximum (MERID. CONV. +), which corresponds to the stage between panels −5 and 0 in Figs. 3 and 4. It can be seen in Fig. 4 that the enhanced convergence at this time can largely be attributed to the Pacific Ocean sector. In the meantime, the region of enhanced precipitation has expanded eastward into the western Pacific Ocean, leading to a maximum of tropical mean precipitation about another 3–4 days later (PRECIP+, 0-lag panels in Figs. 3 and 4).

In Fig. 5a it can be seen that a signal in temperature and zonal wind emanates from the region of maximum precipitation and propagates rapidly eastward in the upper troposphere, so that the tropical mean upper-tropospheric temperature reaches its maximum 4–5 days after the maximum precipitation (MSU34+, bottom panel in Fig. 3). At about the same time the maximum in zonal mean equatorial zonal wind (U200+) is reached, consistent with equatorial β-plane geostrophy. Note, however, that a zonal mean acceleration requires zonal momentum flux convergence, likely to be induced by the superposition of the waves upon the climatological mean circulation as discussed by Weickmann and Sardeshmukh (1994), so that the equatorial warming can not be interpreted as the cause of the westerly acceleration.

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2 Considering an area average of outgoing longwave radiation over the Indian Ocean (60°S–95°E, 10°S–10°N) increases coherence squared with the tropical mean precipitation to 0.22. The MJO index used by Knutson and Weickmann (1987), based on upper-level velocity potential fields with a strong wavenumber 1 signature, exhibits generally higher coherence with our time series.

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Fig. 8. Schematic of the phase relation between reference variables during an intraseasonal event based on results from cross-spectral analysis presented in Table 1. Lags in days assume that a full cycle is 50 days in length.
Global angular momentum reaches its maximum 6–7 days after the equatorial upper-level zonal mean wind. The reason for this phase lag is not clear, but it is in agreement with results of Hendon (1995). As the front in the upper-tropospheric westerly wind anomalies propagates eastward around the globe and reaches the Indian Ocean (Fig. 5a), convection there reaches its minimum (OLR85E+) about another 3–4 days later, that is, about 14 days after the maximum in tropical mean precipitation. The fact that the lag from minimum OLR85E to maximum OLR85E, obtained by adding up the lags between the various independent variables, yields 24 days—that is, about half of the assumed period of 50 days—confirms the reliability of the results of the cross-spectrum analysis.

5. Discussion and conclusions

The intraseasonal variability of tropical mean temperature and precipitation has been shown to be closely linked to the MJO by use of lag regression analysis. The series of lag regression maps generated using tropical mean precipitation or temperature as reference variables corroborate the structure and evolution of the MJO previously documented by Knutson and Weickmann (1987) and Hendon and Salby (1994). The fact that these maps can be retrieved using a variety of tropical mean quantities as reference variables, without the need for spatial filtering or conditional sampling in the time domain, attests to the strength of the relations between the tropical mean quantities and their links to the MJO. The existence of these linkages is confirmed, and phase relations are documented by the results of cross-spectrum analysis, which show statistically significant coherences for the broad 30–60 day band among the zonal means of satellite-derived temperatures and precipitation, and indices of the zonally averaged meridional circulation and zonal wind. Coherences between the new indices and previously used indices (OLR85E, GAM) are weaker, though statistically significant.

The differing strengths of the coherences can be understood considering the different nature of these indices; the low coherences with the reference time series used here do not imply that they are of inferior quality as MJO indices. Different indices emphasize different aspects of the MJO. The OLR85E index, anchored in the region with the most prominent intraseasonal signal in convection, provides a clear picture of an eastward propagating MJO event over the Indian Ocean. The zonal mean indices, aside from being influenced by factors not directly related to the MJO, relate to a later stage of an MJO event and tend to emphasize the planetary-scale aspects of the MJO. GAM is partly influenced by extratropical processes, and as indicated in Fig. 8, the part related to the MJO pertains to the end of a rather long sequence of related events and is less directly related to events earlier in the sequence.

The importance of the zonal mean component of the MJO was illustrated by considering the difference in the appearance of equatorial lag/longitude sections derived from the regression analysis with and without the zonal mean component (Figs. 5 and 6). When the zonal mean is removed, the atmospheric response to enhanced precipitation associated with the MJO seems to be partitioned into two phase speed regimes. This partition is in agreement with the notion of a forced and a freely propagating mode in the eastern and western hemispheres, respectively, which has been considered previously by Knutson et al. (1986), Lau and Peng (1987), Gutzler and Madden (1989), and Hendon and Salby (1994), among others. In these studies the phase speed of the free mode has been documented to be on the order of 10–20 m s\(^{-1}\); the results suggest that the upper-tropospheric response changes its character from a forced to a free mode as it propagates into the western Hemisphere and the precipitation anomaly dies out. Considering the full anomalies, including their zonal mean component, provides a picture in agreement with results of Heckley and Gill (1984) and Jin and Hoskins (1995). They modeled the tropospheric response to the switch-on of an equatorial heat source and found a Kelvin wave front to propagate eastward at a speed of 45–50 m s\(^{-1}\).

Recently Milliff and Madden (1996) detected an eastward propagating signal with a propagation speed of \(-40 m s\(^{-1}\) and a first baroclinic vertical structure over the eastern Pacific, which they associate with the free mode response to enhanced convection associated with the MJO. Our finding of a temperature signal in a deep upper-tropospheric layer with the same rate of propagation is consistent with their observational results, as well as with the model response to the switch-on of equatorial heating in the form of a Kelvin wave front. Considering the atmospheric response to enhanced precipitation, associated with the MJO, from the viewpoint of a transient response to a switched on heat source mandates consideration of the total fields, including the zonal mean component, rather than a decomposition in terms of zonal wavenumbers. The anomalies associated with the eastward propagating Kelvin wave front have a growing zonal mean component and their propagation is characterized by the movement of the wave front. The phase speeds of the zonal wavenumber components of the wave front, considered individually, contain little information about the front’s propagation. The efficient and fast warming of the entire Tropics in response to the enhanced precipitation in the MJO is also consistent with the notion of a Kelvin wave front; sinking at the wave front induces adiabatic warming.

By redistributing the latent heat released in regional convective systems over the tropical belt, Kelvin wave fronts associated with the transient atmospheric response to the onset of latent heating may be instrumental in maintaining the high degree of spatial homogeneity that is observed in tropical tropospheric temperature on a wide range of timescales. For in-
Fig. 9. Simultaneous regression maps of (a) MSU34, and (b) MSU23 temperatures onto tropical mean (20°S–20°N) tropospheric temperature calculated from MSU2. The maps are scaled to represent the anomalies associated with a positive deviation of one standard deviation in the reference time series. Contour interval 0.1 K; the zero contour is thickened.

stance, observational studies based on radiosonde data (Newell and Weare 1976; Angell 1981; Horel and Wallace 1981; Navato et al. 1981; Pan and Oort 1983; Angell 1988) and on satellite-derived temperature data (Yulaeva and Wallace 1994) have shown that a major part of the atmospheric response to ENSO events is a warming of the tropical troposphere as a whole. Figure 9 shows the simultaneous regression maps of monthly MSU34 and MSU23 onto the tropical tropospheric mean temperature (1000–200 mb), retrieved from MSU channel 2. In analogy with the temperature responses presented in Fig. 3, a temperature anomaly reminiscent of the Gill response can be seen, which is associated with increased precipitation over the anomalously warm surface waters of the central Pacific during an ENSO event (Yulaeva and Wallace 1994). As in the intraseasonal temperature response, the warming of the Tropics as a whole is much more prominent at upper-tropospheric levels (MSU34) than at lower levels (MSU23).

The typical warmings that occur in response to an ENSO or MJO event are ~0.5 K and ~0.15 K, respectively. Considering the above-mentioned homogeneity of the tropical temperature field and comparing these amplitudes to the amplitude of the climatological mean annual cycle for upper and lower troposphere of 0.4 K and 0.6 K, respectively, the responses are of appreciable magnitude. Nevertheless, it should be pointed out that with an amplitude of only 0.15 K we do not expect the temperature response to an MJO event to have a large impact on the stability characteristics of the tropical troposphere. In particular, it seems unlikely that such small fluctuations would be capable of modulating tropical convection to a significant degree.

Still, the documented very fast equatorial signal could serve as a possible explanation for the observed high degree of homogeneity of the tropical atmospheric temperature, and deserves a more detailed description. Anomalous, satellite-derived water vapor channel temperature, a proxy for large-scale subsidence, might prove useful for this purpose.

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