Length of Day Changes Associated with the Madden–Julian Oscillation

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ABSTRACT

The previously reported spectral peak near 50 days in time series of length of day (LOD) is shown to occur in conjunction with episodes of tropical convective activity associated with the Madden–Julian oscillation (MJO). When the convective signal of the MJO is absent, LOD exhibits a red spectrum at intraseasonal timescales. LOD is shown to be in phase with the convective anomaly due to the MJO over the date line and out of phase with the convective anomaly over the Indian Ocean. A composite angular momentum budget, made relative to the convective signal of the MJO, reveals that the zonal surface stress only partially accounts for the observed tendency of LOD. Not only is the amplitude some 50% too weak, the phase is shifted ahead of the LOD tendency by about $^1/_8$ cycle. Hence, in order to balance the angular momentum budget, an additional mountain torque is postulated to occur. This additional torque is required to lag the frictional torque by about $^1/_4$ of a cycle, but be of similar amplitude.

The composite surface stress anomalies appear to result predominantly from zonal mean zonal wind anomalies. An important role for the zonally symmetric convective anomaly due to the MJO is suggested. The surface zonal wind anomalies at low latitudes, which exhibit a high degree of equatorial symmetry with zero amplitude on the equator, appear to be accounted for as the linear response to zonal mean convective heating in the presence of strong dissipation. The upper-tropospheric zonal wind anomalies, which mimic the angular momentum anomalies, are not accounted for by simple linear momentum balance. In particular, maximum zonal wind anomaly occurs on the equator, which suggests an important role for eddy fluxes of momentum during the life cycle of the MJO.

1. Introduction

Atmospheric angular momentum exhibits a spectral peak near 50-day period (e.g., Rosen and Salstein 1983). Similar fluctuations in the length of day (LOD) have been reported (e.g., Langley et al. 1981) that reflect conservation of the angular momentum of the earth–atmosphere system. An increase in atmospheric angular momentum is accompanied by a decrease in the rotation rate of the earth and hence an increase in the length of day. Fluctuations with a period of about 50 days are also prominent in the tropical circulation (e.g., Madden and Julian 1971). These tropical fluctuations are associated with eastward-propagating anomalies of convection and zonal wind (e.g., Madden and Julian 1972) and are commonly referred to as the Madden–Julian oscillation (MJO). Fluctuations of winds, surface pressure, and convection associated with the MJO are highly coherent with the near 50-day period fluctuation of atmospheric angular momentum and LOD (Madden 1987; Dickey et al. 1991; Weickmann et al. 1992; Magana 1993). Furthermore, the fluctuation of atmospheric angular momentum appears to originate in tropical latitudes, where the signal of the MJO is the strongest, and propagates poleward (Anderson and Rosen 1983; Dickey et al. 1991; Magana 1993). Thus, the tropical MJO appears to be at the root of the 50-day period fluctuation of atmospheric angular momentum and LOD.

For the intraseasonal timescale considered here, angular momentum is exchanged between solid earth and atmosphere by either frictional torques or pressure (mountain) torques (e.g., Lambeck 1980). The budget for the globally integrated atmospheric angular momentum can be expressed as

$$\frac{\partial M}{\partial t} = T_f + P, \qquad (1)$$

where M is the atmosphere's angular momentum, T_f is the frictional torque, and P is the pressure torque. Madden (1988) has shown, using data from a single season, that frictional torques, due to anomalous wind stress over the tropical Pacific associated with the eastward passage of the MJO, are large enough to account for the observed tendency of M at near 50-day period. Enhanced surface easterlies across the tropical Pacific are presumed to supply a torque to the solid earth; a quarter cycle later M and LOD maximize. The surface easterlies increase as anomalous convection moves from the

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Indian Ocean eastward toward the date line. However, more recent studies have suggested that frictional torques due to surface stress anomalies in the Tropics are not adequate to fully account for the observed tendencies in Weickmann et al. (1992) and Madden (1992), while not explicitly calculating a budget, inferred this from the phase relationship between angular momentum and lower-tropospheric zonal wind anomalies composited over the life cycle of the MJO. In a case study of the angular momentum budget for a single 65-day period (which apparently is dominated by one large cycle of the MJO), Weickmann and Sardeshmukh (1994) found that the contribution by mountain torques was as large as that by surface frictional torques.

The present study aims to clarify the role of frictional stresses associated with the MJO for producing near 50-day fluctuations of M and LOD. In contrast to previous studies, the role of the surface stress will be quantified by computing a budget for angular momentum over a composite life cycle of the MJO for the extended period 1979–1989. Here, only the time series of LOD is considered, from which concomitant fluctuations of M are estimated. The approach taken is to isolate those periods when the signal of the MJO in the tropical circulation is present and when it is not. The LOD time series is examined during these contrasting periods to determine how much of the spectral peak in the 50-day band results from behavior while the signal of the MJO is present. It is found that the spectral peak at 50 days in LOD only occurs when the signal of the MJO is present. To shed light on how the MJO causes this fluctuation in LOD, composites of the LOD variations, its tendency, and surface stress variations are created over the life cycle of the MJO. In this fashion the angular momentum budget (1) over the life cycle of the MJO can be evaluated. Composites of zonally averaged winds, divergences, tropospheric mean temperature, and outgoing longwave radiation (OLR) are also created so that the mechanism for the exchange of momentum between atmosphere and earth may be better understood.

2. Data and method

The circulation anomalies associated with the MJO are described using standard meteorological fields for the period 1979–1989. These include horizontal winds and divergences at 1000, 850, and 200 mb. Daily averages from ECMWF analyses are used for the period 1980–1989 and NMC analyses are used for 1979. Brightness temperatures from channel 2 of the microwave sounding unit (MSUT) are used to estimate tropospheric mean temperatures (for example, see Spencer and Christy 1992a,b). The broad weighting of MSUT makes this channel an excellent indicator of the deep baroclinic temperature anomaly associated with the simple baroclinic structure of the MJO (Madden and Julian 1972). OLR from the NOAA polar-orbiting satellites is used as a proxy for convective activity. The OLR data have been converted to equivalent blackbody temperature (brightness temperature), which is indicative of cloud-top temperature. The sign convention used here is that a negative temperature anomaly is defined as a positive deviation (i.e., enhanced convection). All of these data are available daily (MSUT has been interpolated from 5-day averages) on a 5.6° longitude by 2.8° latitude grid.

Wind stress and frictional torque are estimated from the daily 1000-mb winds. While stress computed from operational analyses is most suspect in the Tropics (e.g., Trenberth et al. 1989), the computation of stress from analyzed winds is generally regarded as the best available option for underobserved areas such as over the tropical oceans. Furthermore, Madden (1992) has shown consistent estimates of intraseasonal stress calculated from ECMWF analyses and the independent Global Band Analyses from the Fleet Numerical Oceanographic Center. Nonetheless, the calculation of stress from operational analyses is recognized to be imprecise, and the results presented here need to be assessed in light of these uncertaintities. The stress, at longitude λ and latitude θ, is approximated by

$$\mathcal{T}_x(\lambda, \theta) = -\rho C_d u[V], \qquad (2)$$

where u is the zonal wind, $[V]$ is the magnitude of the total wind, C_d is the drag coefficient $= 1.5 \times 10^{-3}$, and ρ is the air density at the surface $= 1.2$ kg m^{-3}. The frictional torque about the polar axis, produced by the stress (2) acting on a 5.6° longitude by 2.8° latitude grid box at (λ, θ), is

$$T_f = a^3 \cos^2(\theta)\mathcal{T}_x(\lambda, \theta)\delta\lambda\delta\theta, \qquad (3)$$

where a is the radius of the earth, $\delta\lambda = 2\pi/64$, and $\delta\theta = \pi/64$.

To represent the change in the earth's angular momentum, the Jet Propulsion Laboratory daily time series of LOD for 1979–1989 has been obtained (e.g., Eubanks et al. 1985). On timescales less than one year, changes in the rotation rate of the earth are driven mainly by the atmosphere (Lambeck 1980). Changes in LOD thus imply changes in atmospheric angular momentum and are equated empirically as

$$\mathrm{LOD}' = 1.68 \times 10^{-26} M', \qquad (4)$$

with LOD′ in milliseconds (ms) and the change in atmospheric angular momentum M' in kilograms per squared meter per second (Langley et al. 1981).

Episodes of significant convective activity associated with the MJO are determined as in Salby and Hendon (1994, hereafter SH94). They showed that the signal of the MJO in tropical convection occurs predominantly during December–April, is confined mainly within about 10° of the equator, and is broadband in wavenumber and frequency (i.e., eastward wavenum-

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bers 1–3 with periods 35–95 days). Note that this range of periods is broader than is traditionally associated with the dynamical components of the MJO (e.g., Madden and Julian 1971). SH94 developed a window function to isolate these episodes of significant behavior. The window function has unit magnitude for all significant periods and is zero otherwise. Time series of LOD and other circulation parameters are multiplied by this function prior to spectral analysis. Records for which this function have been applied are referred to as windowed records. To isolate episodes when the convective signal is absent, the complement of this function is used; these records are referred to as complementary records. Prior to creating the windowed and complementary records, the time series of LOD and other fields are subjected to a high-pass filter that only passes fluctuations with periods less than 150 days. This prefiltering is required because the average duration of a significant episode is about 150 days. Hence, fluctuations with periods longer than 150 days appear as trends in the subrecords and thus need to be removed. Note also that the application of this window broadens the effective bandwidth and decreases the effective degrees of freedom within the intraseasonal band; see SH94 for further discussion.

3. LOD spectrum and coherence with tropical circulation

The spectra of unwindowed (solid), windowed (long dash), and complementary (dotted) LOD are shown in Fig. 1. Raw spectral estimates were computed by Fourier analysis. The raw spectra were then smoothed with a Gaussian filter, with an effective bandwidth as shown. Also shown is the 95% confidence limits for the smoothed spectral estimate at a 50-day period for the unwindowed record. The confidence limits were determined using a chi-square test with 15 degrees of freedom (dof) assumed for each smoothed spectral estimate. The dof were estimated using the technique of Blackman and Tukey (1958). Their technique leads to an estimation of about 60 dof in the 38–70-day band. This band contains about 50 spectral estimates, thus about 1.2 dof are associated with each spectral estimate (which is significantly smaller than 2 dof if each spectral estimate is assumed to be independent). A smoothed spectral estimate contains about 13 raw estimates; hence, about 15 dof are associated with each smoothed estimate.

A broad spectral peak near 50-day period is evident in the unwindowed spectrum [see also Magana (1993) for an estimation of its significance using a finer bandwidth]. This broad peak (roughly 38–70 days) is hereafter referred to as the 50-day band. This peak is even more marked in the windowed record. In contrast, the spectrum from the complementary record appears red at these frequencies. Thus, the spectral peak near 50 days results from fluctuations in LOD that occur while the signal of the MJO in tropical convection is present. Dickey et al. (1991) reached a similar conclusion using a different approach.

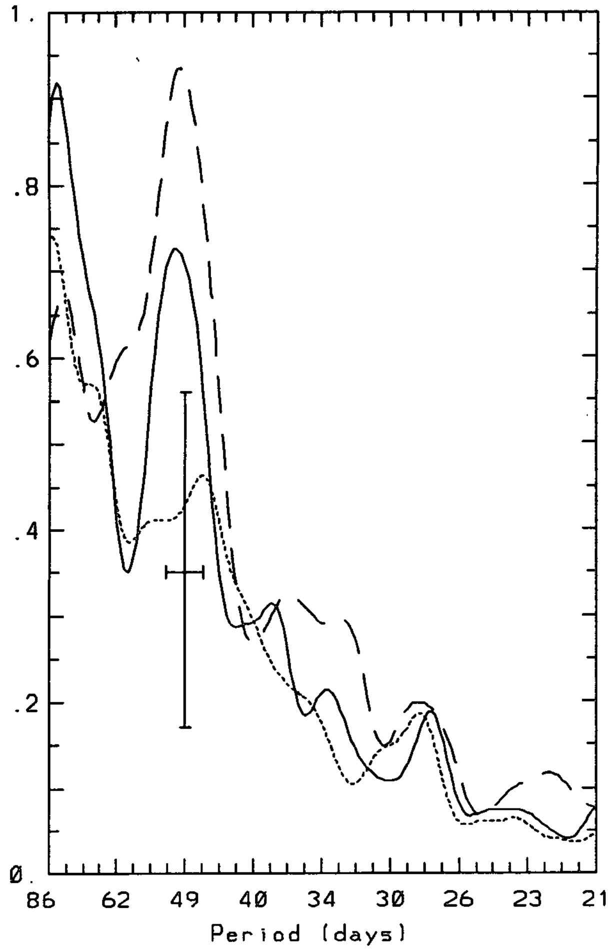

FIG. 1. Spectrum of LOD for total record (solid), windowed record (long dash), and complementary record (dotted). Spectra are normalized by the total power at periods less than 150 days. Vertical bar indicates the 95% confidence limits for the spectral estimate at 50-day period for the unwindowed record. Horizontal bar indicates effective bandwidth.

The relationship between the 50-day fluctuations in LOD and convection is investigated by computing their coherence band using windowed data. The coherence squared between LOD and the time series of OLR at each grid point, filtered to wavenumbers 1–3 (the wavenumbers for which the signal of the MJO in convection is concentrated; see SH94), is shown in Fig. 2. Peak coherence squared of about 0.3 to 0.4 occurs along the equator over the Indian Ocean and the western Pacific. Phase arrows indicate that the LOD time series is out of phase with convection over the Indian Ocean and in phase with convection near the date line (see also Weickmann et al. 1992). Systematic eastward propagation, with phase speed of about 3–5 m s^{-1}, is evident for the convection, which reflects the behavior

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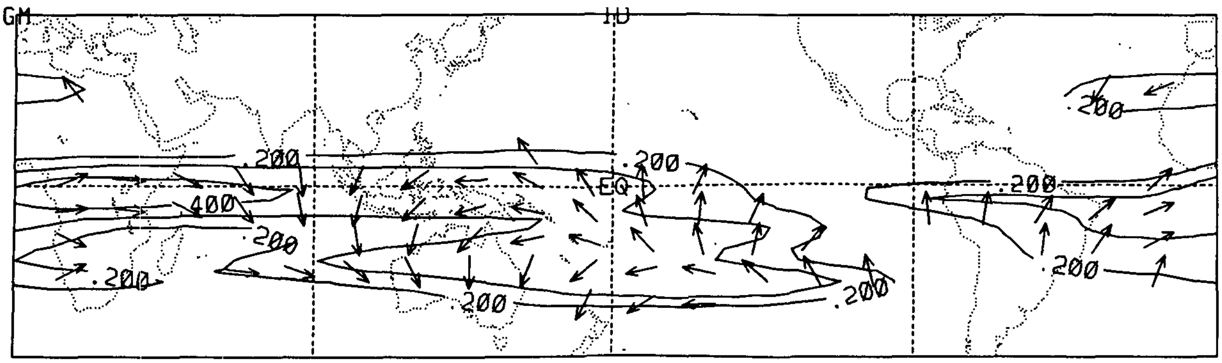

FIG. 2. Coherence squared (contours) and phase angles (arrows) between windowed LOD and OLR filtered to eastward wavenumbers 1–3 in the 50-day band. Contour interval for coherence squared is 0.1 and the first contour is at 0.2, which is significant at the 95% level. Upward pointing arrows indicate LOD is in phase with OLR locally. Downward pointing arrow indicates an out of phase relationship. Clockwise rotation of the arrows from west to east indicates eastward propagation.

of the MJO as it propagates eastward from the Indian Ocean toward the date line (e.g., Hendon and Salby 1994; hereafter HS94). The peak coherence of 0.3–0.4 implies that 30%–40% of the windowed variance of LOD in the 50-day band is accounted for by the eastward-propagating convection associated with the MJO. This amount of variance is roughly equivalent to the amount of power in the LOD spectrum that stands out above the background spectrum (Fig. 1), which further corroborates the conclusion that the behavior of the MJO is responsible for the 50-day period signal in LOD. Furthermore, coherences between LOD and OLR during complementary periods are some 70%–80% weaker (not shown).

4. Composite evolution

a. Global M budget

Linear regression analysis is used to create a composite angular momentum budget (1) over the life cycle of the MJO. As the information required to compute the pressure torque was not readily available, only the LOD tendency and frictional torque are estimated. The frictional torque is computed by summing (3) over all longitudes from pole to pole. The composites are made as in HS94, except here the more limited frequency band of 38–70 days is considered (as determined from the breadth of the spectral peak in LOD). HS94 created the composite life cycle from data filtered to 35–90

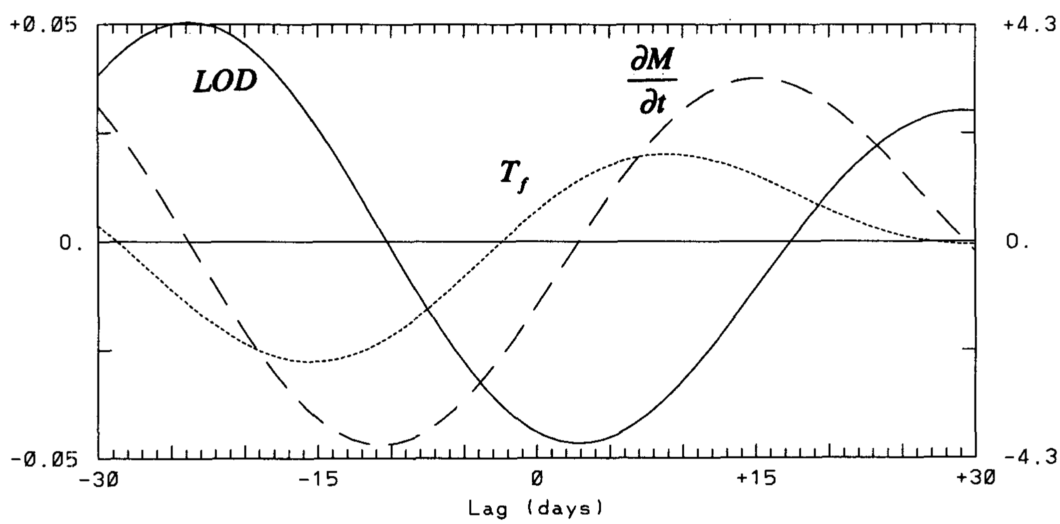

FIG. 3. Lag composite of LOD (solid) formed by regressing windowed LOD onto OLR at (0°, 85°E) in the 50-day band. Units of LOD are in ms (left-hand ordinate). Equivalent angular momentum tendency (long dash) and composite surface stress (dotted) have units of 10^{18} kg m^2 s^{-2} (right-hand ordinate). Anomalies are shown for a one standard deviation of OLR at the base point.

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days, which was dictated by the breadth of the peak in OLR spectrum.

The composite budget is created by regressing windowed time series of LOD and frictional torque onto the windowed time series of the propagating component (wavenumbers 1–3) of OLR at the grid point near (0°, 85°E). Composite anomalies are shown for a one standard deviation fluctuation of OLR at (0°, 85°E); see SH94 for further details.

The regressed time series of LOD is shown in Fig. 3 (solid line) as a function of lag. The minimum occurs near lag 0, or when the convection is maximum near 90°E (Fig. 1; see also Madden 1987, 1988; Weickmann et al. 1992). The amplitude of the LOD fluctuation (solid line) is about 0.05 ms (left-hand ordinate). The equivalent fluctuation in atmospheric angular momentum is, from (4), about 2.9×10^{24} kg m^2 s^{-1}. This magnitude is about half as large as that for the event discussed by Madden (1988). However, the event he examined displayed particularly large amplitude. If a two standard deviation OLR anomaly at (0°, 85°E) is used to normalize the regression coefficients, then the magnitudes would be nearly identical.

The tendency of the LOD fluctuation (long dashed line in Fig. 3) is formed by centered differencing of the composite LOD fluctuation. The units for the LOD tendency are on the right-hand ordinate. The dotted line is T_f, the regressed frictional torque integrated over the globe. If this frictional torque were the sole cause of the change in angular momentum, then it should be in phase with the tendency in LOD. Rather than being in phase with the LOD tendency, the frictional torque leads it by 6–7 days.[1] Thus, instead of T_f being in quadrature (i.e., leading by 1/4 cycle or about 12 days) with the LOD time series, T_f leads LOD by about 3/8 cycle (18–20 days). Madden (1992) found an almost identical phase lag. The amplitude of the composite frictional torque is also only 60% of the observed tendency in LOD. That the frictional torque accounts for just more than one-half of the observed LOD tendency is also in accord with estimates made from much shorter records (e.g., Madden 1987, 1988).

It is an interesting exercise to construct a hypothetical time series of the additional torque required to balance the angular momentum budget. Here M is observed (from Fig. 3) to vary as

$$M = M_o e^{i\omega t}, \qquad (5)$$

with $\omega = 2\pi/50$ days. The composite frictional torque is observed (Fig. 3) to vary as

$$T_f = 0.6 M_o i\omega e^{i(\omega t + 2\pi/8)}. \qquad (6)$$

Substitution of (5) and (6) into (1) yields

$$P = 0.7 M_o i\omega e^{i(\omega t - 2\pi/8)}.$$

Thus, balancing the momentum budget requires an additional torque, P, with amplitude approximately *equal* to, but with phase about 1/4 of a cycle *behind,* the observed frictional torque. In a study of the angular momentum budget for one cycle of the MJO, Weickmann and Sardeshmukh (1994) diagnosed frictional and pressure (mountain) torques with just such behavior.

b. *Zonal integrals*

The contribution from different latitude bands to the global integral of T_f is examined by considering the composites of T_f as function of latitude (Fig. 4). Positive maxima in torque occur at 15°–20° latitude around day +5. Near-zero torque occurs along the equator, and poleward propagation is apparent with substantial torque occurring as far poleward as 45° latitude. Essentially no torque is evident poleward of about 50° latitude.

The composite zonal mean 1000-mb zonal wind is shown in Fig. 5. Note that the latitudinal range is only 45° N–S, which is where the frictional torque is limited. As compared to T_f, maxima occur farther poleward (centered near 30° latitude), which is consistent with the geometric $\cos^2$ term in T_f. As with T_f, the zonal wind displays near-zero amplitude on the equator, symmetry about the equator, and poleward propagation away from the equator.

Also shown in Figs. 4 and 5 is the composite zonal mean OLR anomaly (enhanced convection shaded). Its amplitude is about 1/6 to 1/7 that of the propagating component (cf. Figs. 1–5 in HS94). The potential role of this zonal mean convective anomaly for driving the observed low-latitude stress fluctuation is discussed below. Here it will only be mentioned that this zonal mean anomaly is out of phase with the angular momentum fluctuation (cf. Fig. 3; see also Riseby and Stone 1988). It is also in phase with the 1000-mb zonal wind anomaly at low latitudes and with the eastward-propagating component of convection at 90°E, as can be inferred by comparison with Fig. 2. This is better seen by examining the coherence and phase of eastward-propagating (zonal wavenumbers 1–3) OLR at each grid point with the zonal mean OLR at the equator (Fig. 6). Peak coherence squared, in the 50-day band, is greater than 0.4 across the Indian and western Pacific Oceans. The zonal mean convective anomaly is in phase with the propagating component of convection near 90°E and out of phase near the date line (note the similarity with Fig. 2, but with reversed phase). This result suggests that the zonal mean convective anomaly results from the localized enhancement of the clima-

[1] This phase difference is just significant at the 95% level. The significance was determined by calculating the confidence intervals for the phase between OLR at (0°, 85°E) and LOD and for the phase between OLR at (0°, 85°E) and T_f in the 35–75-day band. According to Jenkins and Watt (1968, 381), the 95% confidence limit for the phase between OLR and LOD is ±2.5 days and is ±3.5 days for the phase of between OLR and T_f.

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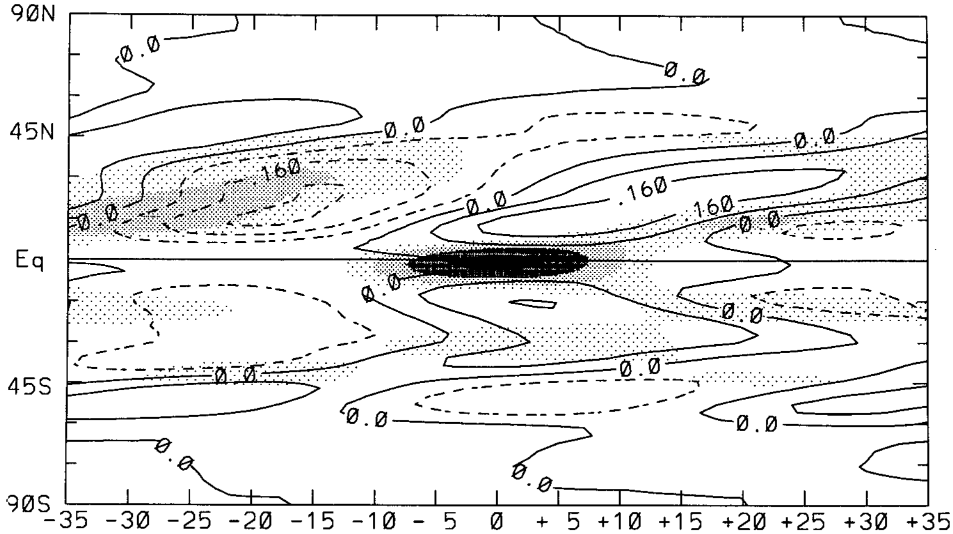

FIG. 4. Composite zonal mean frictional torque anomalies (contours) and OLR brightness temperature (shading) as functions of lag (days) and latitude formed by regressing windowed frictional torque onto OLR at (0°, 85°E) in the 50-day band. Contour interval is 0.08×10^{18} kg m^2 s^{-2}. Positive convective anomalies are shaded at 0.1, 0.3, 0.5, and 0.7 K.

tological convection over the Indian Ocean (e.g., SH94) by the MJO.

Anderson and Rosen (1983) showed that the dominant contribution to the 50-day period fluctuation of M comes from the zonal winds in the tropical upper troposphere. The composite zonal wind at 200 mb is shown in Fig. 7. Maximum easterlies near the equator occur near day 0, concomitant with minimum M, which can be inferred from the minimum LOD (Fig. 3). Note also that the occurence of maximum winds on the equator is in contrast to those at 1000 mb, which are near zero there. The 200-mb zonal winds also display some symmetry about the equator, although the anomalies south of the equator are markedly stronger than those just north of the equator. The latitudinal structure of the 200-mb zonal wind anomalies agrees well with the latitudinal structure of the observed 50-day period fluctuations in angular momentum as diagnosed by Dickey et al. (1991; see their Fig. 20). In particular, primary maxima occur between 10°–15° latitude, which are in phase with globally integrated M, poleward propagation in the Northern Hemisphere is evident, and secondary maxima of opposite sign occur near 30° latitude.

As in aid in interpreting the evolution of M and the surface stress, composites of other aspects of the circulation are considered. The 1000-mb divergence is shown in Fig. 8a. Equatorial surface convergence is seen to lag zonal mean convection by about 5 days (1/10 cycle). This is in sharp contrast to the propagating component of the MJO, which has the surface convergence leading convection by about 1/3 of a cycle (HS94). The zonal mean surface convergence also mimics the poleward propagation of convection, which thus supports the realism of this feature. The composite divergence at 200 mb (not shown) displays similar features but with opposite sign.

Figure 8b displays the composite meridional wind at 1000 mb. The zonally averaged meridional wind is antisymmetric about the equator with convergent equatorward flow flanking the 1000-mb convergence and convection. This structure is anticipated from the 1000-mb divergence (recall that zonally symmetric divergence is produced entirely by the zonally symmetric meridional wind). Note too that poleward propagation of the meridional wind in the Northern Hemisphere is apparent. Finally, the composite MSUT is shown in Fig. 9. Low-latitude MSUT anomalies are centered on and symmetric about the equator. Minimum M (near day +2) occurs very near the node in this equatorial temperature anomaly. Note that negative MSUT anomalies lead the zonal mean convection and surface convergence by about one-quarter of a cycle. Maxima in the extratropical temperature anomalies occur near 30° latitude and are nearly in phase with those at the equator. Some symmetry about the equator is apparent, although the anomalies in the Southern Hemisphere are stronger than those north of the equator. Also, some evidence of poleward propagation is seen north of about 20°N.

5. Discussion

In a recent study, Weickmann and Sardeshmukh (1994) emphasized the role of the eddy component of the MJO for causing the observed fluctuation of angular momentum. On the other hand, they discounted the

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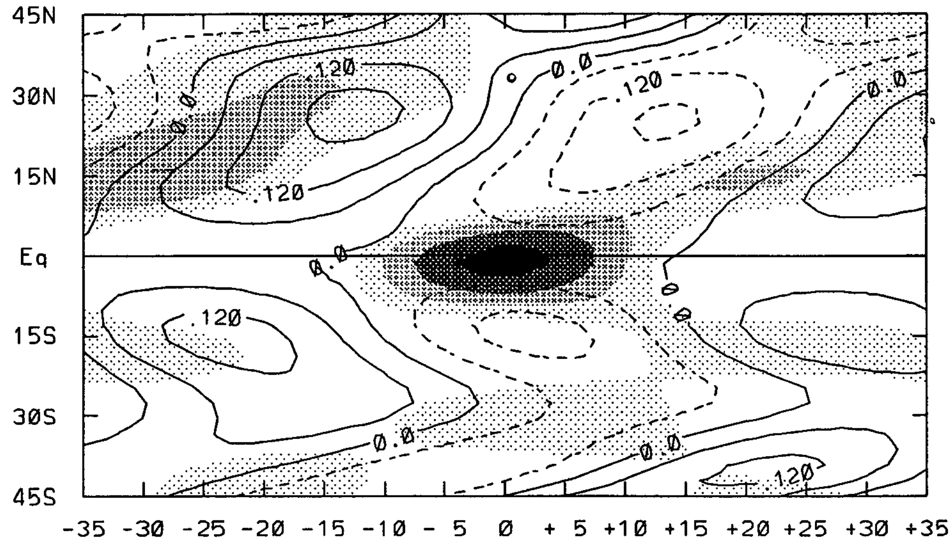

FIG. 5. As in Fig. 4 except for zonally averaged 1000-mb zonal wind. Contour interval is 0.06 m s^{-1}.

possible role of zonal mean convective heating anomalies for directly forcing zonal mean circulation anomalies, and, in particular, for forcing zonal mean stress anomalies that may directly result in frictional torque. The results presented in section 4, however, seem to suggest an important role for such anomalies of zonal mean convective heating, at least for the low-latitude frictional torque.

The similarity between the zonal mean OLR and surface divergence anomalies (Fig. 8a) with regard to their phases, latitudinal structure, and poleward propagation all suggest that indeed the zonal mean OLR anomalies are indicative of zonal mean convective heating anomalies. While the magnitude of the zonal mean OLR anomaly is significantly weaker than that of the eddy component of the MJO, this in itself does not preclude an important role for this zonal mean forcing. That relatively small zonal mean heating may cause a relatively large zonal mean wind anomaly at low latitudes can be inferred from consideration of the vorticity balance in the Tropics. For zonally asymmetric heating localized near the equator and for timescales long compared to the frictional decay time, the low-level flow in the vicinity of the heating is in Sverdrup balance (e.g., Gill 1980). That is, the generation of vorticity by vertical stretching associated with the heating-induced convergence is predominantly balanced by *poleward* planetary vorticity advection. Hence, to a large degree, small relative vorticity anomalies are generated because of the substantial cancellation between these two terms. On the other hand, a Sverdrup balance is not possible in the zonal mean. As all of the zonal mean convergence results from *equatorward* meridional convergence, the planetary advection and stretching terms will act together and hence generate a large relative vorticity anomaly.

The composite zonal mean T_f (or, equivalently, stress) anomalies (Fig. 4) do indeed appear to result from the linear response of the surface winds to imposed zonal mean heating. From Fig. 8b, it can be inferred that the zonal mean heating, which to first order is centered on and symmetric about the equator, drives equatorially symmetric meridional surface convergence. Similarly, negative zonal mean heating anomalies drive meridional surface divergence. If frictional processes in the boundary layer are adequately approximated as Rayleigh friction, then for frictional timescales short compared to the 50-day timescale of the MJO, the linearized (about a state at rest) zonal mean zonal momentum equation is

$$-f[v] = -\mathcal{K}[u],$$

where brackets indicate a zonal average and $\mathcal{K}$ is the Rayleigh friction coefficient. The surface zonal wind should be in phase (out of phase) with the Coriolis term, $f[v]$, north (south) of the equator, exhibit similar meridional structure as the meridional wind, and be zero on the equator (due to the vanishing of f). The 1000-mb zonal wind displays all of these characteristics. Finally, the similarity of the T_f and surface zonal wind anomalies suggest that the T_f anomalies result simply from fluctuations of zonal mean zonal wind anomalies.

Needless to say, this simple linear argument in no way fully explains the observed fluctuation in M. On the one hand, the angular momentum fluctuation mimics the upper-level zonal wind, which has maxima on the equator (Fig. 7). These maxima cannot possibly result from the linear response to zonal mean heating for a basic state at rest. It is also unlikely that this linear argument accounts for the poleward propagation of the low-level zonal wind anomalies and, hence, the ob-

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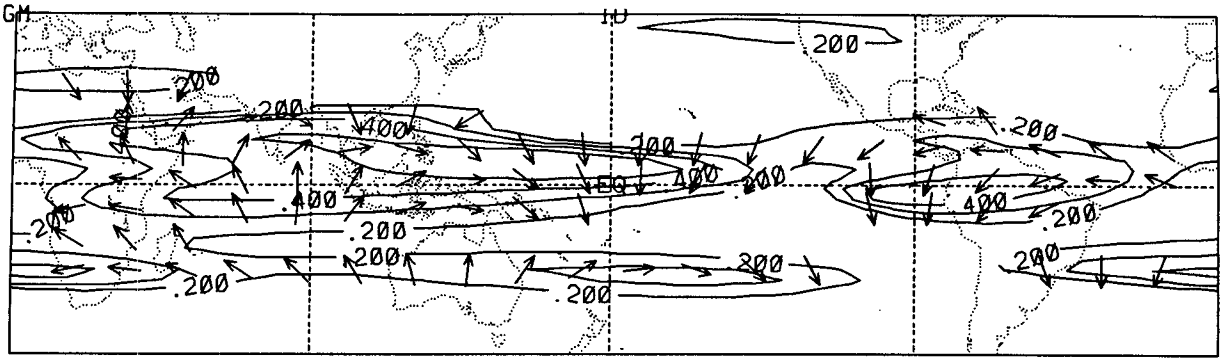

FIG. 6. Coherence squared and phase between windowed zonal mean OLR and eastward-propagating (wavenumbers 1–3) OLR at each grid point in the 50-day band. Plotting is as in Fig. 2.

served anomalies poleward of about 30° latitude. Furthermore, the composite T_f anomalies were shown to be inadequate to account for the observed length of day tendency. Not only was the magnitude too weak (which may be underestimated from the bulk formula used here), but the phase was wrong as well. All of these discrepancies point to a first-order role for the eddy component of the MJO.

The convergence of eddy momentum flux onto the equator likely accounts for the upper-tropospheric zonal wind anomalies on the equator (e.g., Itoh 1994). Localized surface pressure anomalies, resulting from wave propagation away from the convective activity over the Indian and western Pacific Oceans, probably account for the mountain torques (Weickmann and Sardeshmukh 1994). Nonetheless, it appears that the role of zonal mean heating anomalies for directly forcing low-latitude zonal mean circulation anomalies, which in turn play an important role in the angular momentum cycle, cannot be ruled out.

6. Summary and conclusions

The spectral peak near 50-day period in LOD was shown to occur in conjunction with episodes of tropical convective activity associated with the MJO. These episodes occur predominantly during northern winter when the signal of the MJO in convection is best defined and the coherence between the convective anomalies and circulation anomalies are strongest (SH94). When the signal of the MJO is absent, the LOD spectrum is red at intraseasonal frequencies, strongly suggesting a causative role of the MJO for the observed near 50-day period LOD fluctuations.

A composite angular momentum budget over the life cycle of the MJO was created for the extended period

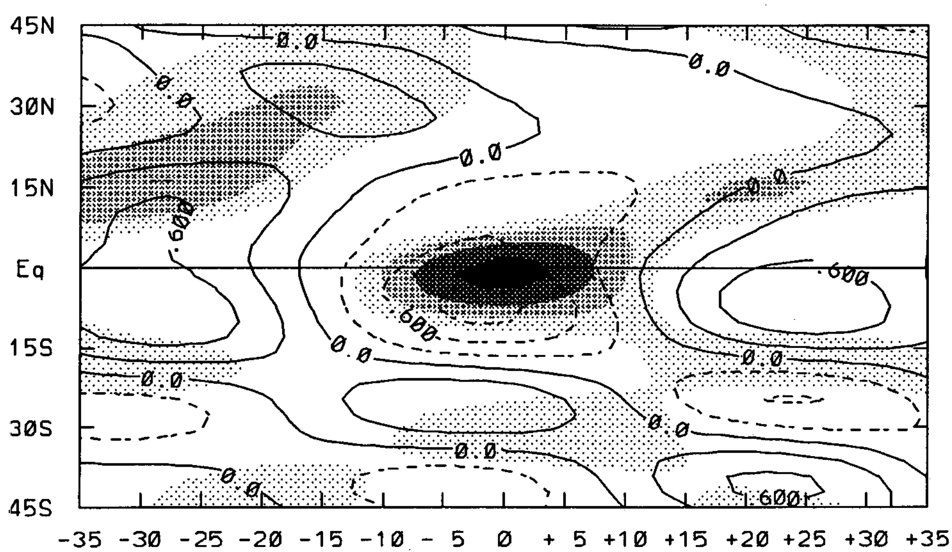

FIG. 7. As in Fig. 4 except for zonally averaged 200-mb zonal wind. Contour interval is 0.3 m s^{-1}.

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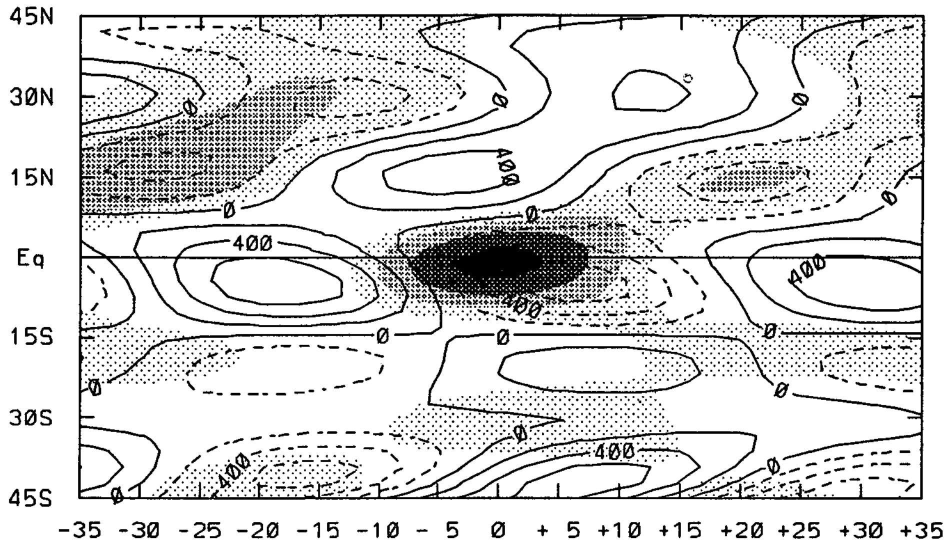

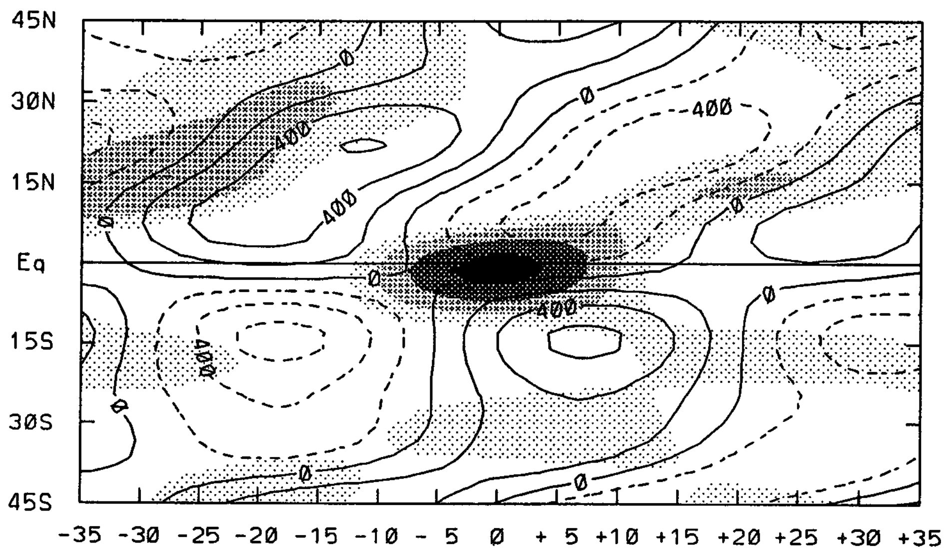

FIG. 8. As in Fig. 4 except for (a) zonally averaged divergence and (b) meridional wind at 1000 mb. Contour in (a) is 0.2×10^{-7} s^{-1} and in (b) is 0.02 m s^{-1}.

1979–1989. The only torque explicitly considered was that due to surface stress anomalies. If this torque were the sole mechanism for causing the observed fluctuation in LOD, then it should display similar magnitude and be in quadrature with the equivalent fluctuation in M. Only about one-half of the M anomaly can be explained by the frictional torque due to the MJO. Not only is the frictional torque some 50% too small, its phase is shifted ahead of quadrature by about 1/8 of a cycle. While significant frictional torque was found between 30° and 45° latitude, these results concur with Madden (1993), who only considered stresses equatorward of 30° latitude. On the other hand, Weickmann and Sardeshmukh (1994) found the predominant frictional torque to occur *poleward* of about 45°N. However, it is not clear in their study of a single 65-day period what is signal associated with the MJO and what is unrelated midlatitude variability.

Although a likely mechanism exists for rapidly communicating the frictional stress from the ocean surface to the solid earth (Ponte 1990), another torque of equal magnitude but with phase shifted 1/8 of a cycle behind quadrature appears to be required to explain the observed change in LOD. Weickmann and Sardeshmukh (1994) found the pressure torque to be of similar magnitude as the frictional torque and to be shifted in phase about 1/3 of a cycle behind the frictional torque. This is similar to the magnitude and phase shift of the additional torque deduced here to balance the momentum budget.

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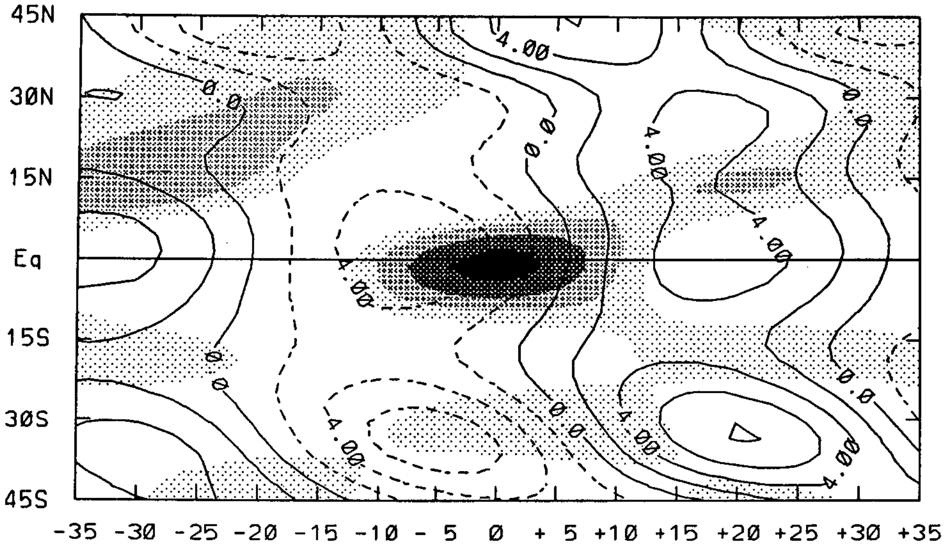

FIG. 9. As in Fig. 4 except for zonally averaged MSUT. Contour interval is 0.02 K.

Two possibilities for the generation of this mountain torque via localized surface pressure anomalies are suggested. The first is due to meridional Rossby wave propagation away from the convective activity over the Indian and western Pacific Oceans toward the Himalayas (e.g., Weickmann and Sardeshmukh 1994). The localization of the observed extratropical Rossby gyres associated with the MJO to this region (e.g., HS94) suggest this is a distinct possibility. The second possibility is the interaction of the equatorial Kelvin component of the MJO, which rapidly radiates into the western hemisphere away from the convective activity west of the date line (e.g., HS94), with the Andes Mountains. Further observational and model analyses are required to address this issue.

The evolution of the low-latitude composite frictional torque appears to be reasonably accounted for by evolution of the zonal mean surface winds. In turn, the low-latitude zonal mean surface winds seem adequately explained as the linear response to the zonal mean component of convective heating centered on the equator associated with the MJO. Zonal mean heating presumably arises from the confinement of the propagating component of convection to two centers of action over the Indian Ocean and the western Pacific (see SH94). Away from the frictional boundary layer, this linear interpretation breaks down. Nonzero 200-mb zonal winds are observed on the equator, which is a violation of the linear momentum balance for heating centered on the equator. Hayashi and Miyahara (1987) noted similar behavior in their linear response model of the MJO. Nonlinear eddy fluxes of momentum, due to the propagating component of the MJO (e.g., Magana and Yanai 1991) and advection by the mean meridional circulation (Weickmann and Sardeshmukh 1994), however, cannot be ruled out.

Poleward propagation of the composite zonal mean perturbations is also observed. The poleward propagation also may possibly be accounted for by meridional advection due to the Hadley circulation. Furthermore, poleward propagation is a characteristic of the low-frequency, zonally symmetric eigenmodes of the primitive equations linearized about a realistic Hadley circulation (Anderson and Stevens 1987).

This poleward propagation appears to be important for affecting the observed 50-day period fluctuation in angular momentum. Whereas peak heating, divergence, and temperature perturbations occur near the equator, peak wind stress occurs some 20° off the equator. This wind stress is due predominantly to fluctuations of the trades across the Pacific basin, in agreement with Madden (1987). However, the stress extends well into the subtropics as a result of the poleward propagation of the zonally symmetric 1000-mb winds. The stress poleward of 30° latitude makes an important contribution to integrated frictional torque and thus needs to be understood in order to account for the momentum exchanges associated with the MJO.

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