Why Are the Climatological Zonal Winds Easterly in the Equatorial Upper Troposphere?

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ABSTRACT

Using 16 years of NCEP–NCAR reanalysis data on the 200-mb surface, it is shown that in the deep Tropics, the horizontal transient eddy momentum flux *accelerates* the zonal mean zonal wind. This acceleration is mainly due to transient eddies of intraannual and interannual timescales, and to those associated with the Madden–Julian oscillation (MJO). The interannual timescale eddy fluxes are dominated by eastward-propagating disturbances with zonal wavenumber 2 and a period of 2–4 yr, suggesting that these eddy fluxes may be tied to the El Niño–Southern Oscillation.

In the deep Tropics, the single most important factor that decelerates the zonal mean zonal wind is the horizontal momentum flux divergence due to the transient meridional circulation associated with seasonal cycle of the Hadley cells. The deceleration by the transient meridional circulation is much greater than the acceleration due to the transient eddies. This result indicates that a nonzero obliquity of the earth is crucial for maintaining the present climate's equatorial easterlies.

Consistent with the above findings, in an idealized GCM with a fixed equinox insolation and a sea surface temperature field symmetric across the equator, the tropical upper-tropospheric zonal wind is *westerly*. This is in part because such a GCM does not retain a transient meridional circulation arising from the seasonal cycle and because the horizontal eddy momentum flux convergence due to the MJO is stronger than that in the observations.

1. Introduction

Understanding the climatological general circulation has been a major challenge in large-scale atmospheric dynamics. In recent years, a combination of axisymmetric circulation theories (Schneider 1977; Held and Hou 1980; Lindzen and Hou 1988) and theories and observations of midlatitude wave activity (Simmons and Hoskins 1978; Held and Phillips 1987; Edmon et al. 1980, among others) have formed a basic paradigm for understanding elements of the climatological zonal mean general circulation. Namely, axisymmetric circulations establish Hadley cells and subtropical jets, and meridional propagation of midlatitude eddies, generated by baroclinic instability and stationary wave sources, accelerates[1] the midlatitude zonal mean zonal winds and decelerates the zonal mean zonal winds on the equatorward flank of the subtropical jets, as the waves are absorbed near their critical latitudes (e.g., Held and Phillips 1987; Feldstein and Held 1989). It appears that a general understanding of the tropical upper-tropospheric easterlies is built on both Hide's theorem (Hide 1969; Held and Hou 1980) in the context of axisymmetric circulations and the absorption of midlatitude wave activity on the equatorward side of subtropical jets (Suarez and Duffy 1992).

This view, that the momentum flux divergence of the midlatitude-generated eddies contributes to the upper-tropospheric tropical easterlies, appears to be consistent with the observed momentum fluxes shown by Oort and Peixoto (1983) (see also Peixoto and Oort 1992). They presented the time mean zonal mean momentum flux, $[\overline{uv}]$, decomposed into three components:

$$[\overline{uv}] = [\overline{u'v'}] + [\overline{u}^*\overline{v}^*] + [\overline{u}][\overline{v}], \qquad (1)$$

where the square brackets denote zonal mean, asterisks the deviation from the zonal mean, overbars the time mean, and primes the deviation from the time mean. The three terms on the right-hand side (rhs) of (1) are the momentum flux by the transients, the stationary eddies, and the mean meridional circulation (hereafter MMC), respectively. It is important to note that $[\overline{u'v'}]$ is composed of the sum of the transient eddy momentum flux $[\overline{u'^*v'^*}]$ and the transient meridional momentum

[1] In this study, the term acceleration (deceleration) refers to an eastward (westward) acceleration.

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flux $\overline{[u]'[v]'}$. Oort and Peixoto (1983) show that in both hemispheres, except for $10°S < \phi < 0°$ above 500 mb, where ϕ is the latitude, $[\overline{u'v'}]$ is poleward between the equator and 50°, with its maxima at 30° and 200 mb. This implies that the transients cause a momentum flux divergence on the equatorward side of the subtropical jets, appearing to be consistent with barotropic decay of midlatitude eddies (e.g., Simmons and Hoskins 1978; Edmon et al. 1980) and suggesting that $\overline{[u]'[v]'}$ makes an unimportant contribution toward $[\overline{u'v'}]$. This presumption might have been further enhanced because the meridional structure of $[\overline{u'^*v'^*}]$ for intraseasonal timescale transients (e.g., see Randel and Held 1991) is indeed consistent with that of $[\overline{u'v'}]$. However, to our knowledge, there has been no study that separately examines $\overline{[u]'[v]'}$ and $[\overline{u'^*v'^*}]$, spanning synoptic to interannual timescales, which can either verify or refute the above view.

By performing such an analysis, this study will show that the above presumption is incorrect. For the transient eddy momentum flux, we will show that it is not the midlatitude-generated eddies, but the eddies associated with the Madden–Julian oscillation (MJO) (Madden and Julian 1971, 1972), intraannual,[2] and interannual timescales that dominate in the deep Tropics. In fact, it will be shown that the transient eddies associated with the MJO, intraannual, and interannual timescales *accelerate* the tropical zonal mean zonal winds. Also, in the Tropics, the transient meridional circulation is far from being negligible; instead, we will show that the transient meridional circulation associated with the seasonal cycle plays a crucial role in the deceleration of the zonal mean zonal winds, contributing toward the maintenance of the tropical upper-tropospheric easterlies. The above role of the transient eddy fluxes is particularly intriguing given that an atmosphere with an equatorial superrotation (i.e., westerlies over the equator) can be obtained in a two-layer GCM, if there is a zonally asymmetric equatorial heat source above a certain threshold value (Suarez and Duffy 1992; Saravanan 1993).

Data and analysis methods are described in section 2, followed by results in section 3. Section 4 presents results from an idealized GCM that complement the findings in section 3. The conclusions are presented in section 5.

2. Data and analyses

The data used in this study are the daily National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis covering 1980–95. We chose to analyze the 200-mb horizontal winds because the momentum fluxes reach their maxima close to this level in the Tropics. The original data are converted to rhomboidal spectral truncation at wavenumber 30. A detailed description of this dataset can be found in Kalnay et al. (1996).

The main results of this study can be succinctly presented by space–time cross-spectral analyses. Because this analysis method has been described and applied to the momentum flux in previous studies (e.g., Hayashi 1982; Zhangvil and Yanai 1980; Randel and Held 1991), only a brief description is given here. First, in order to identify robust characteristics in our analysis, the 16 yr of data are divided into two 8-yr periods, 1980–87 and 1988–95, giving a 2922-day time series for each period. For each latitude, the zonal and meridional winds, u and v, are decomposed into both frequency and zonal wavenumber space by a Fourier transform. Then the covariance spectra of $[\overline{uv}]$ is calculated for a given frequency and zonal wavenumber. This spectra is smoothed using a normalized Gaussian spectral window with a bandwidth of $10\Delta\omega$, where $\Delta\omega$ is the unit frequency interval of $2\pi/2922$ days. Once these covariance spectra are obtained, it is straightforward to calculate $\overline{[u]'[v]'}$ and $[\overline{u'^*v'^*}]$ for any zonal wavenumber and frequency by simply adding the power spectral density (hereafter PSD) at appropriate frequencies and zonal wavenumbers. We confirmed that the above four components of the momentum flux, obtained from the PSD, reproduce the corresponding quantities calculated in the gridpoint space and time domains.

As will be shown below, the seasonal cycle plays a dominant role in the transient meridional momentum flux ($\overline{[u]'[v]'}$) and its convergence. Because smoothing of the spectra inevitably spreads the large spectral power at the seasonal timescale into surrounding frequencies, the seasonal cycle of the horizontal winds are removed before the space–time cross-spectral analyses are performed. For each of the 8-yr periods, the seasonal cycle is obtained by calculating the climatological value for each calendar day, followed by a smoothing with a 60-day low-pass digital filter. The results are insensitive to the choice of the cutoff frequency. Also, tapering is applied for each of the 8-yr periods in order to remove any artificial long-term trends.

3. Results from the reanalysis data

a. Horizontal momentum flux

Figures 1a and 1b show the four components of the momentum flux ($[\overline{u}][\overline{v}]$, $[\overline{u}^*\overline{v}^*]$, $\overline{[u]'[v]'}$, and $[\overline{u'^*v'^*}]$), and the corresponding meridional momentum flux *convergences* for $23.5°S \leq \phi$ 23.5°N at 200 mb. First, one notes that $[\overline{u}][\overline{v}]$ is not symmetric about the equator. This is because the point that separates the two branches of poleward outflow of the Hadley cells lies at 7°N, rather than at the equator. Second, $[\overline{u'^*v'^*}]$ changes sign near 10° in both hemispheres, resulting in an acceleration of the zonal mean zonal wind within $4°S \leq \phi \leq$

[2] We use the term *intraannual* to denote timescales greater than one season and less than one year. Therefore, the intraannual timescale does *not* include the seasonal cycle.

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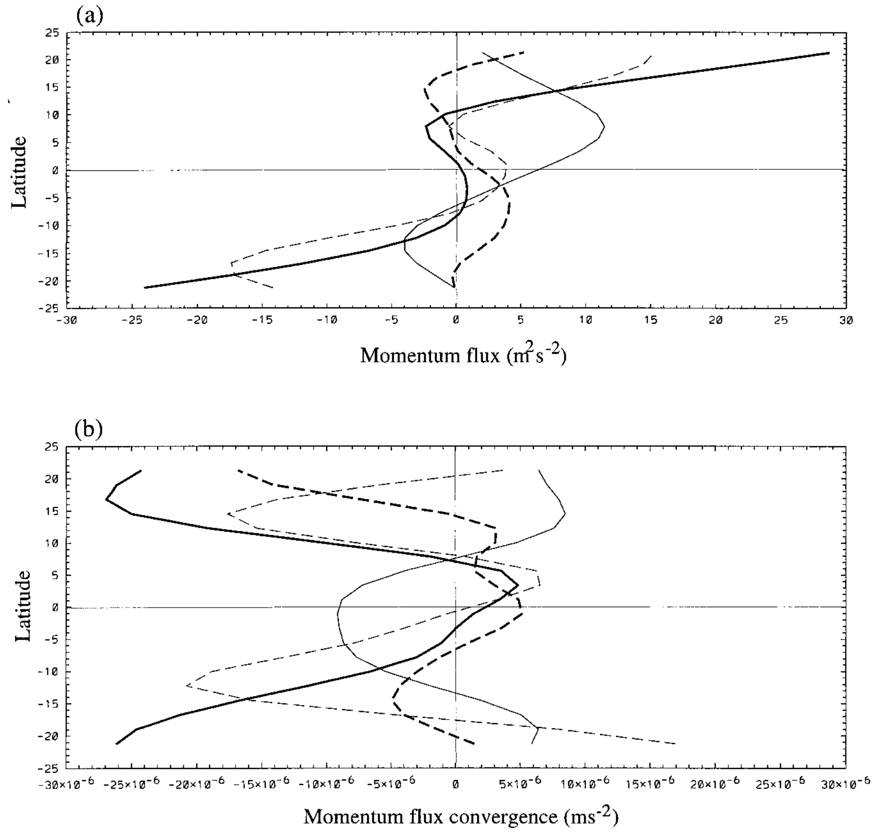

FIG. 1. (a) Momentum fluxes and (b) momentum flux convergences by transient eddies (thick solid line), stationary eddies (thick dashed line), transient meridional circulation (thin solid line), and mean meridional circulation (thin dashed line) at the 200-mb level.

8°N (see Fig. 1b). The maximum value of this acceleration is comparable to that due to the convergence of $[\overline{u}^*\overline{v}^*]$ and $[\overline{u}][\overline{v}]$ in the deep Tropics. This result is clearly at odds with what one would expect if the dominant influence was from eddies that propagate from midlatitudes toward the equator. Third, between 15°S and 15°N, the value of $\overline{[u]'[v]'}$ is greater than that of $[\overline{u'^*v'^*}]$. More importantly, the momentum flux convergence due to the transient meridional circulation decelerates the zonal winds more than the acceleration caused by any of the other three components. Thus, the *net* effect of the transient meridional circulation and transient eddies is to decelerate the zonal winds at the equator, consistent with the results of Oort and Peixoto (1983). On the other hand, it should be noted that in the subtropics the transient eddies do decelerate the zonal mean zonal winds, and the effect of the transient eddies is greater than that of the transient meridional circulation. Noting that the focus of this paper is on the deep Tropics, however, this subtropical feature will not again be discussed in this paper.

The simple analysis, presented in Fig. 1, clearly demonstrates that in order to understand the climatological zonal mean zonal winds in the Tropics, both the transient eddies and transient meridional circulation should be better appreciated. For this purpose, we examine covariance spectra of $[\overline{u'^*v'^*}]$ and $\overline{[u]'[v]'}$. These covariance spectra are shown in Figs. 2 and 5 for the 1980–87 and 1988–95 periods, respectively.

Figure 2a shows the PSD of $[\overline{u'^*v'^*}]$ as a function of zonal wavenumber and latitude, by integrating over all frequencies. As noted earlier, the seasonal cycle is removed before the PSD is calculated. It is clear that the acceleration by the transient eddies in the deep Tropics is by and large due to zonal wavenumbers (k) 1 and 2. The PSD, integrated over all zonal wavenumbers, displayed as a function of period and latitude, is shown in Fig. 2b. Because there is no well-organized, strong transient eddy momentum flux for periods less than 25 days or so, we only show the PSD for frequencies corresponding to a period that is greater than 20 days. Zhangvil and Yanai (1980) also showed that for periods less than 30 days, which is the longest timescale they considered, there is no well-organized momentum flux in the deep Tropics. In both hemispheres, there are two distinct periods for which equatorward transient eddy momentum fluxes are prominent; one greater than 100 days, another ≈ 50 days. We also note that the intraseasonal timescale disturbance shows clear eastward propagation.

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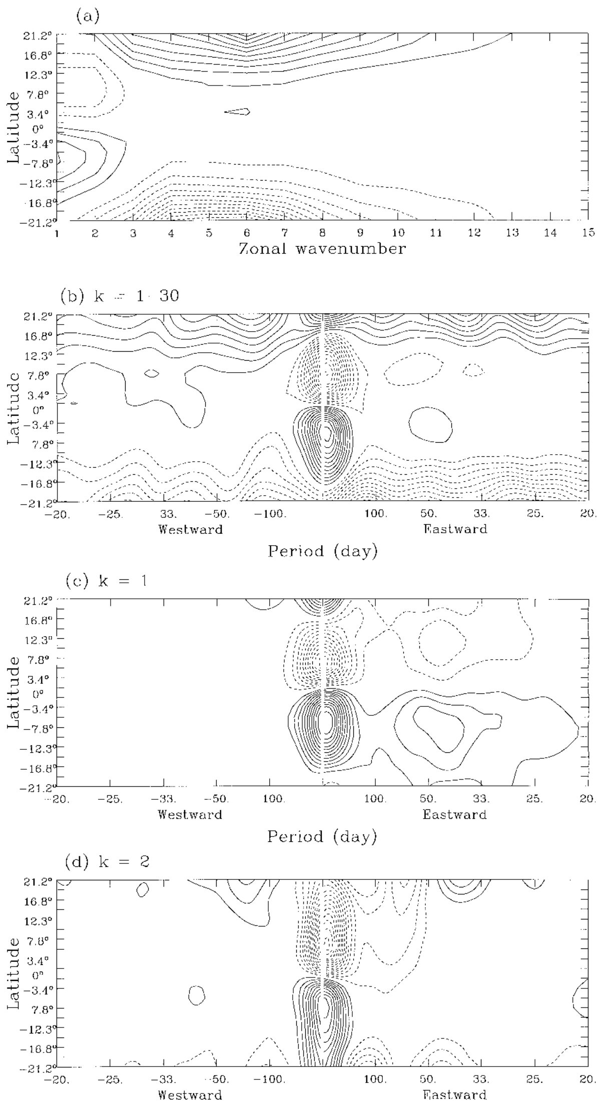

FIG. 2. The PSD of the transient eddy momentum flux for the period of 1980–87, as a function of (a) zonal wavenumber and latitude, integrated over all periods; (b) period and latitude, integrated over all entire zonal wavenumbers; (c) period and latitude, for zonal wavenumber 1; and (d) period and latitude, for zonal wavenumber 2. Solid contours are positive, dashed contour negative, and the zero contour is omitted. Contour interval is (a) 0.3 m² s⁻², (b)–(d) 10⁻² m² s⁻².

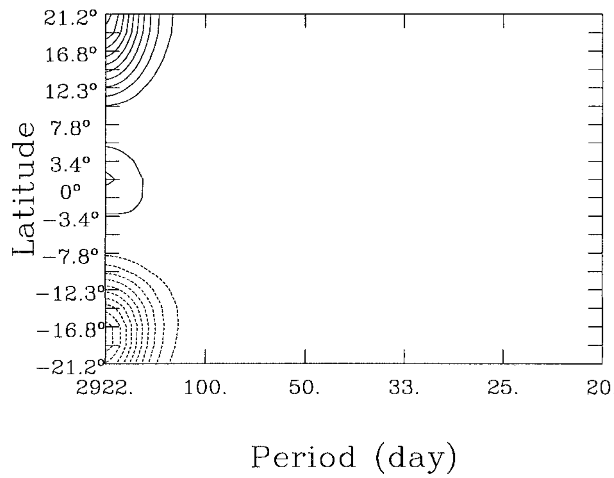

FIG. 3. The PSD of the transient meridional circulation as a function of period and latitude for the period of 1980–87. Solid contours are positive, dashed negative, and the zero contour is omitted. Contour interval is 2×10^{-2} m² s⁻².

Because $k = 1$ and 2 are mainly responsible for the equatorward momentum flux, in order to identify phenomena that account for this direction of the momentum flux, the PSDs are constructed for $k = 1$ and 2 separately and are shown in Figs. 2c and 2d, respectively. For $k = 1$, centered around 12°N and 10°S, equatorward momentum fluxes can be seen at periods between approximately 30 and 70 days, associated with an eastward-propagating feature. These characteristics are consistent with velocity potential spatial scale, period, and direction of propagation of the MJO (Knutson and Weickmann 1987), suggesting that in the time and zonal mean, the MJO pumps westerly momentum into the deep Tropics. If one accepts that zonally asymmetric heating associated with the MJO can act as a wave source, the above finding may not be too surprising. This is because one expects wave energy to propagate away from a source region, hence a divergence of group velocity from the source region; provided that the meridional potential vorticity gradient is positive, the direction of the eddy momentum flux is opposite to that of the group velocity. Thus, in a region where the group velocity diverges, the eddy momentum flux is expected to converge, accelerating the zonal mean zonal wind.

For both $k = 1$ and 2, two main centers of prominent equatorward transient eddy momentum flux exist at 6°N and 8°S, both with a period of ≈2–4 yr, and propagate eastward. Based on its period and direction of propagation, we speculate that this interannual timescale eddy momentum flux is associated with changes in the geographical distribution of diabatic heating during ENSO events. Precipitation composites by Kiladis and Diaz (1989) show that in the Tropics, during June, July, and August (JJA) of the year that precedes an ENSO event, precipitation maxima occur over Indonesia and the western Pacific, and over the Amazon Basin and western Africa. As the ENSO event progresses, the positive precipitation anomaly over Indonesia and the western Pacific propagates eastward. By JJA of the following year, during which the ENSO signal reaches its maximum, the anomalous precipitation maximum appears in the central Pacific. However, eastward propagation of the other precipitation center, that is, over the Amazon Basin and western Africa, is rather unclear. It is possible that the anomalous heating associated with ENSO events project onto both zonal wavenumbers 1 and 2, producing the equatorward transient eddy momentum flux found for both $k = 1$ and 2.

Figure 3 shows the PSD of the momentum flux due

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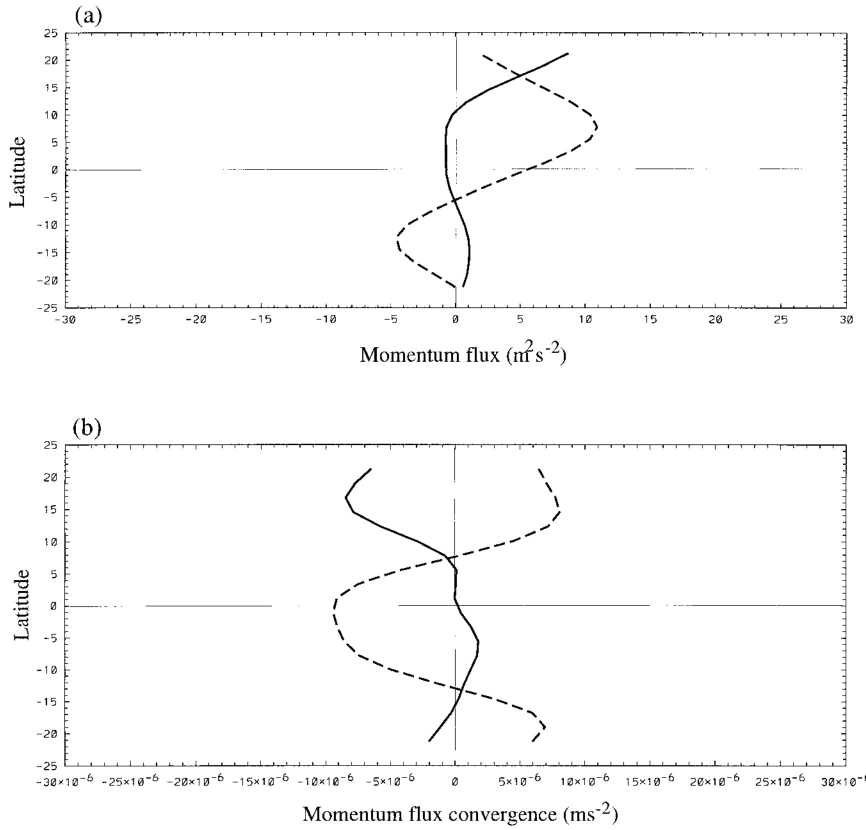

FIG. 4. (a) Momentum fluxes and (b) momentum flux convergences by transient eddies (solid line) and the transient meridional circulation (dashed line) due to the seasonal cycle, for the period 1980–87.

to the transient meridional circulation ($\overline{[u]'[v]'}$). Most of the spectral power appears for periods greater than 100 days, and this component of the momentum flux decelerates the zonal winds in the deep Tropics. However, over the deep Tropics, the maximum negative value of the momentum flux convergence from the transient meridional circulation, summed over all periods except the seasonal cycle, is -2.6×10^{-7} m s^{-2}. This value accounts for only 3% of the deceleration due to the total transient meridional circulation (see Fig. 1b).

Figures 4a and 4b show $\overline{[u]'[v]'}$ and $[\overline{u'^*v'^*}]$ and their meridional *convergences* due to the seasonal cycle. Between the equator and 15°S the transient eddies due to the seasonal cycle accelerate the zonal wind. However, they play only a secondary role in the acceleration of the zonal winds in the deep Tropics (cf. Figs. 1b and 4b).

Both $\overline{[u]'[v]'}$ and its meridional convergence due to the seasonal cycle show remarkable resemblance to their total counterparts [cf. thin solid line in Fig. 1a (1b) and dashed line in Fig. 4a (4b)], indicating that over the deep Tropics the seasonal cycle almost entirely explains $\overline{[u]'[v]'}$ and therefore the deceleration of the zonal winds. Because $\overline{[u]'[v]'}$ in the Tropics comes from the variability of the Hadley cells, the above result indicates that the seasonal cycle of the Hadley cells is crucial for maintaining the equatorial easterlies. In light of this result, it is interesting to note that equatorial easterlies are stronger in a nonequinoctial axisymmetric circulation (Lindzen and Hou 1988) than in an equinoctial axisymmetric circulation (Held and Hou 1980). Observations (e.g., Peixoto and Oort 1992) support this result, although the equatorial easterlies during solstice conditions are much weaker than those in the steady, axisymmetric circulation obtained by Lindzen and Hou (1988). Such a discrepancy is not surprising given that the analytical solution by Lindzen and Hou (1988) is obtained by imposing a steady, angular momentum-conserving motion combined with the specification of zero zonal wind at the latitude of maximum rising motion, which clearly cannot be applied to the atmosphere in a strict sense.

The key findings for the 1980–87 period, described above, are confirmed by analyses of data for the 1988–95 period. The PSD of $[\overline{u'^*v'^*}]$ (see Figs. 5a and 5b) again show that the equatorward momentum flux is due to $k = 1$ and 2 and to eastward-propagating intraseasonal and interannual fluctuations. Again, as for the 1980–87 period, in the PSD of $[\overline{u'^*v'^*}]$ for $k = 1$ (Fig. 5c), the signature of an equatorward momentum flux by the MJO

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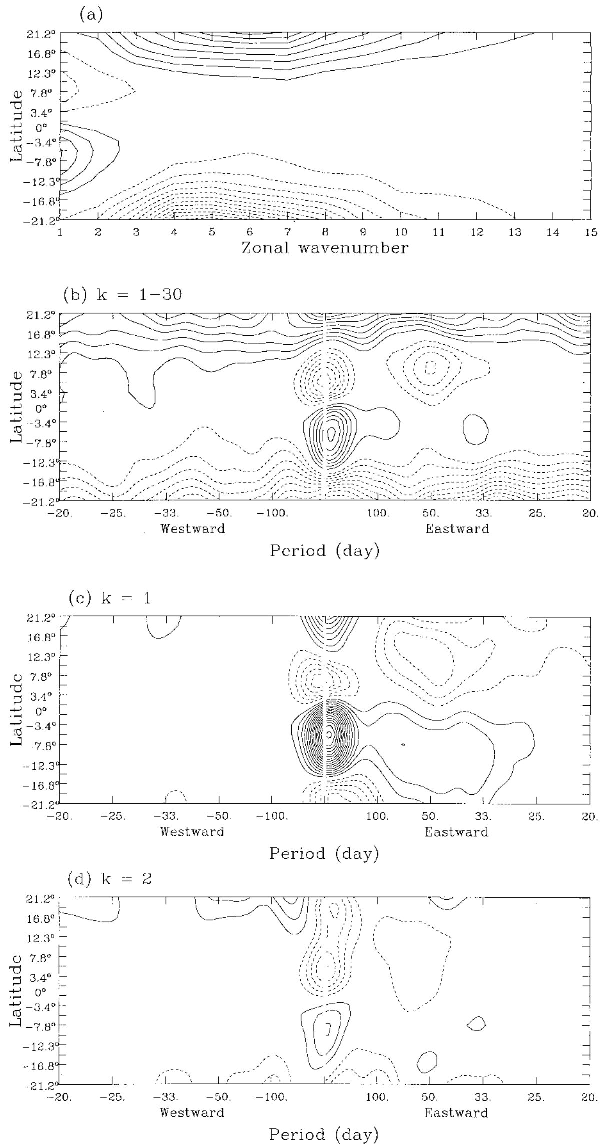

FIG. 5. As in Fig. 2, except for the period 1988–95.

is prominent. However, there is one noticeable difference between the two time periods in that equatorward momentum flux at the MJO timescale appears in $k = 2$ for the 1988–95 period but not for the 1980–87 period. This difference may be explained by the possibility that zonally localized heating might project more strongly onto $k = 2$ during the latter half than during the former half of the analyzed period. As for the 1980–87 period, the momentum flux by the transient meridional circulation is poleward except between the equator and 5°N, with essentially all the power being concentrated in periods greater than 100 days (not shown). In addition, transient momentum fluxes due to the seasonal cycle during this latter 8-yr period (not shown) are found to be essentially identical to those for the 1980–87 period.

Given the robustness of the equatorward momentum flux by the MJO, intraannual, and interannual timescale fluctuations, the transient eddy momentum flux and its convergence are separately calculated for $k = 1$ and 30–70 days, and $k = 1$ and 2, for periods greater than 100 days. In the latter calculation the seasonal cycle is included because the seasonal cycle cannot be neglected in the transient momentum fluxes for $k = 1$ and 2. For reference, however, the transient eddy momentum flux and its convergence for $k = 1$ and 2, arising from the seasonal cycle, is also calculated (Fig. 6). At the equator,[3] the transient eddy momentum flux convergence by all zonal scales and periods is 3×10^{-6} m s^{-2} (see Fig. 1b), while that by the MJO and fluctuations with periods greater than 100 days is 0.6×10^{-6} m s^{-2} and 2.5×10^{-6} m s^{-2}, respectively. This indicates that the sum of the momentum flux convergence associated with these two fluctuations can, by and large, explain the acceleration of the equatorial $[\overline{u}]$ by the total transient eddy momentum flux convergence.

b. Zonal momentum budget

In order to quantitatively assess the role of $[\overline{u'^{*}v'^{*}}]$ and $\overline{[u]'[v]'}$, among other terms, the time mean zonal momentum budget is examined. For completeness, the time mean zonal momentum equation is given below:

$$0 = \frac{\partial[\overline{u}]}{\partial t} = -\frac{\partial([\overline{uv}]\cos\phi)}{a\cos\phi\partial\phi} - \frac{\partial[\overline{u\omega}]}{\partial p} + \frac{\tan\phi}{a}[\overline{uv}] + \frac{[\overline{u\omega}]}{a\rho g} + 2\Omega\sin\phi[\overline{v}] + 2\Omega\cos\phi[\overline{\omega}]/\rho g + F, \qquad (2)$$

where the notations are standard, and the relation $\omega = -\rho g w$ is assumed. The vertical convergence of zonal momentum, $-\partial[\overline{u\omega}]/\partial p$, at 200 mb, is obtained by finite differencing $[\overline{u\omega}]$ at 150 and 250 mb. The sign of $-\partial[\overline{u\omega}]/\partial p$ is negative over the entire domain (not shown), but its magnitude is at least an order of magnitude smaller than that of the horizontal momentum flux convergence, $-\partial([\overline{uv}]\cos\phi)/a\cos\phi\partial\phi$. In addition, the amplitude of all four components—MMC, transient meridional circulation, stationary eddies, and transient eddies—of the vertical momentum flux convergence is at least an order of magnitude smaller than the corresponding components of the horizontal momentum flux convergence.

The sum of the terms on the rhs of (2) that account for a steady, axisymmetric circulation (i.e., the sum of the MMC component of the first four terms and the Coriolis torques) yields 10^{-6} m s^{-2} over the equator. Although this number should be taken with caution due to sparsity of observed data in this region, this result

[3] Because there is no grid point on the equator, the equatorial value is estimated by averaging the values at 1.12°S and 1.12°N.

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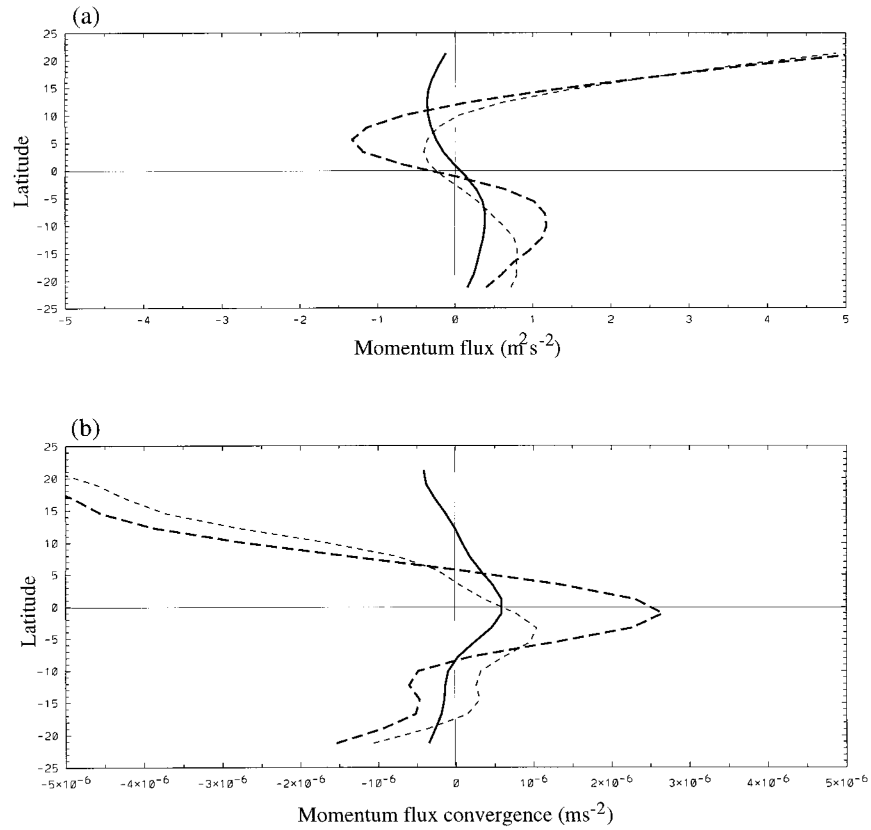

FIG. 6. (a) Momentum fluxes and (b) momentum flux convergences by transient eddies with periods of 30–70 days and $k = 1$ (thick solid line), by transient eddies with periods greater than 100 days and $k = 1$ and 2 (thick dashed line), and by transient eddies due to the seasonal cycle for $k = 1$ and 2 (thin dashed line), for the period 1980–95.

suggests that the observed climatological easterlies in the equatorial upper troposphere should not be interpreted on the basis of Hide's theorem.

4. Results from idealized GCMs

The results from the NCEP–NCAR reanalysis data indicate that in the deep Tropics, the transient meridional circulation due to the seasonal cycle is crucial for maintaining the easterly upper-tropospheric climatological zonal mean zonal wind. On the other hand, transient eddies associated with the MJO and intraannual/interannual timescales can exert an acceleration on the climatological zonal mean zonal wind. Therefore, in an atmosphere where the seasonal cycle is suppressed, while zonally asymmetric heating, such as the MJO, is retained, one might expect to find climatological zonal mean westerlies over the equator. As will be shown below, such a solution is indeed found in an idealized Geophysical Fluid Dynamics Laboratory GCM for which the lower boundary is all ocean, with a prescribed sea surface temperature (SST). In this GCM, the insolation and ozone are fixed at annual mean values. In spite of these idealizations, this GCM contains a full hydrological cycle, including predicted clouds.

The SST distribution of the GCM takes the form

$$\mathrm{SST}(\phi) = \mathrm{SST}_{\mathrm{eq}} - \frac{\Delta T}{2}(\sin^2\phi + \sin^4\phi), \qquad (3)$$

where ϕ is the latitude, $\mathrm{SST}_{\mathrm{eq}}$ the SST at the equator, and ΔT the SST difference between the equator and the poles. Two GCM runs are analyzed here; one will be referred to as the control case, and the other as the uniform warming (hereafter UW) case. For both the control and UW cases, the value of ΔT is fixed at 40 K, while $\mathrm{SST}_{\mathrm{eq}}$ equals 300 and 303 K for the control and UW cases, respectively. Thus, the SST of the UW case is everywhere 3 K higher than that of the control case.

Figure 7a shows $[\overline{u}]$ of the control case, obtained by averaging over 2000 days. The overall structure of $[\overline{u}]$ resembles that of the atmosphere. However, unlike for the atmosphere, in the tropical upper troposphere, $[\overline{u}]$ is westerly; at the equator and at the 200-mb level, $[\overline{u}] = 2.5$ m s^{-1}. Inspection of the momentum flux convergence (Fig. 8b) indicates that these westerlies over

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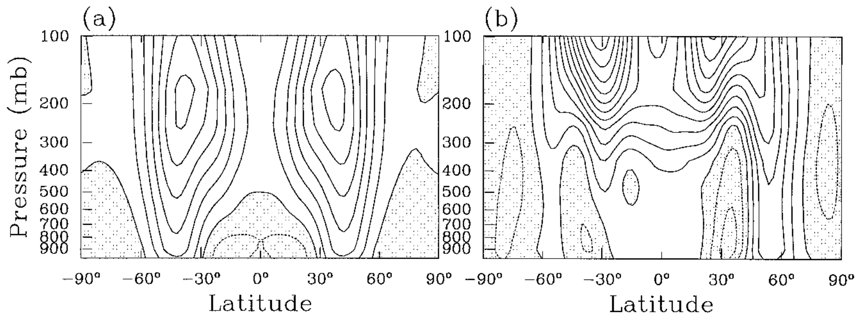

FIG 7. (a) $\overline{[u]}$ for the control case, and (b) $\overline{[u]}$ for the UW case minus $\overline{[u]}$ for the control case. Contour interval is (a) 5 and (b) 0.5 m s^{-1}.

the equator owe their existence to the equatorward momentum flux by the transient eddies (Fig. 8a). The momentum flux convergence by the MMC decelerates $[\overline{u}]$; however, the acceleration by the transient eddies is stronger by a factor of 2, resulting in a net acceleration. In Figs. 8a and 8b, the momentum flux and momentum flux convergence by the transient meridional circulation and stationary eddies are not shown, because they are at least two orders of magnitude smaller than those by the transient eddies and the MMC. This result is not surprising, given that the SST is fixed at equinoctial and zonally uniform values.

In this GCM, the acceleration over the equator is almost entirely due to the model's MJO. For the control case, the PSD of the transient eddy momentum flux indicates that in the Tropics, the equatorward transient eddy momentum flux is completely dominated by disturbances with $k = 1$ (see Fig. 9a) and a peak period of 42 days (Fig. 9b). The PSD, as a function of period and latitude for $k = 1$, clearly captures the signal of

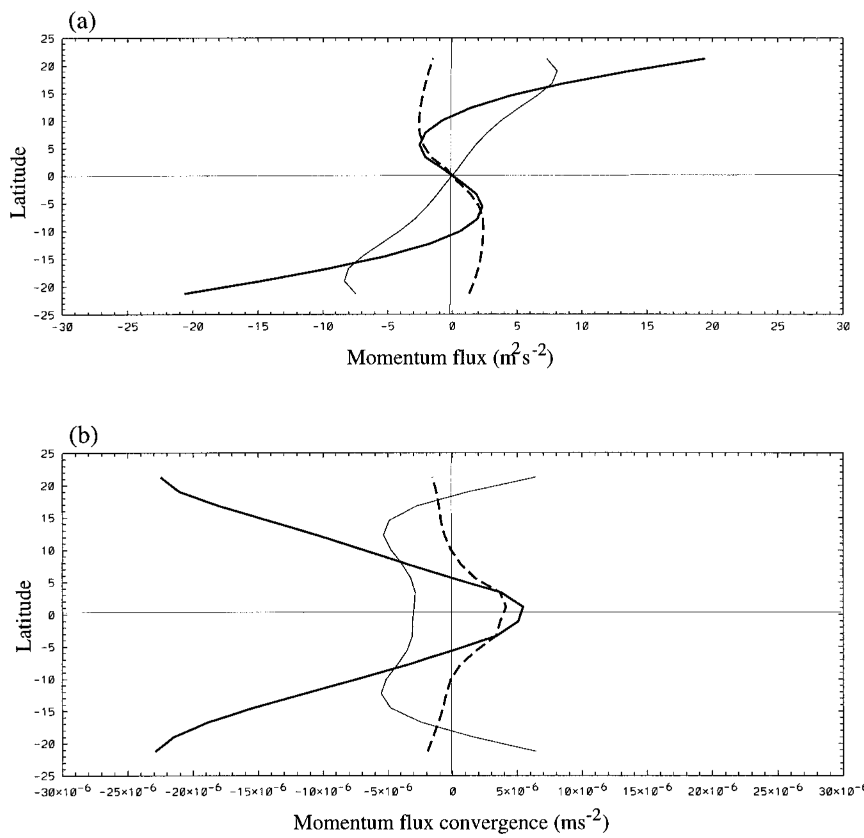

FIG. 8. (a) Momentum fluxes and (b) momentum flux convergences by all transient eddies (thick solid line), transient eddies with periods of 30–70 days (thick dashed line), and mean meridional circulation (thin solid line) for the control case.

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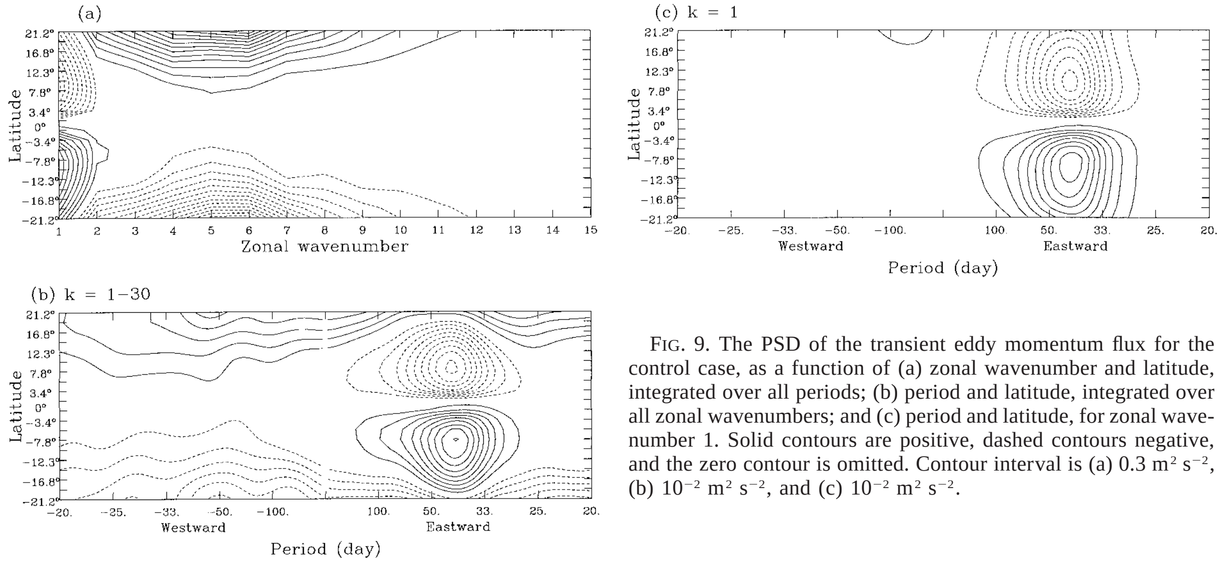

FIG. 9. The PSD of the transient eddy momentum flux for the control case, as a function of (a) zonal wavenumber and latitude, integrated over all periods; (b) period and latitude, integrated over all zonal wavenumbers; and (c) period and latitude, for zonal wavenumber 1. Solid contours are positive, dashed contours negative, and the zero contour is omitted. Contour interval is (a) 0.3 $m^2 s^{-2}$, (b) 10^{-2} $m^2 s^{-2}$, and (c) 10^{-2} $m^2 s^{-2}$.

this 42-day disturbance (Fig. 9c). As will be shown below, this scale and periodicity are consistent with the model's MJO, diagnosed by an empirical orthogonal function (EOF) analysis of the velocity potential. The momentum flux and momentum flux convergence (see thick dashed lines in Figs. 8a and 8b, respectively) for $k = 1$ and a 30–70-day period indicate that the equatorward momentum flux in the Tropics and the acceleration over the deep Tropics are indeed due to the model's MJO. However, it should also be noted that the momentum flux convergence by the MJO in this idealized model is unrealistically strong (cf. Figs. 6b and 8b). Evidently, the climatological westerlies over the equator in this idealized GCM owe their existence to the absence of the seasonal cycle of the Hadley cells and to the unrealistically strong momentum flux convergence associated with the MJO.

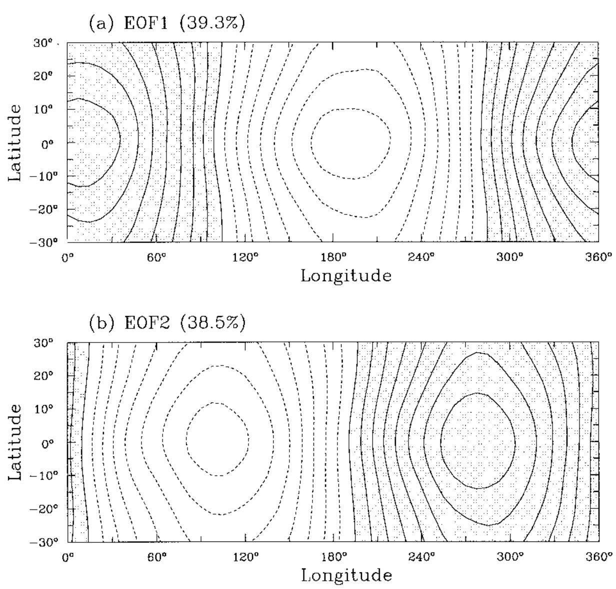

FIG. 10. (a) First and (b) second EOFs of velocity potential for the control case. Solid contours are positive, dashed are negative, and zero contour is omitted. Contour interval is 10^6 $m^2 s^{-1}$.

As stated earlier, in order to confirm that the zonal wavenumber 1 and 42-day period in the transient eddy momentum flux are indeed associated with the model's MJO, an EOF analysis of the velocity potential is performed. Verification of this relationship between the transient eddy momentum flux and the MJO requires that the velocity potential be dominated by the same zonal wavenumber and period. Figures 10a and 10b show the first and second EOFs of the velocity potential, respectively. The first and the second EOFs explain 39.3% and 38.5% of the total variance, respectively; both EOFs are dominated by zonal wavenumber 1; and the principal component of the first EOF lags that of the second EOF by 10 days, with a correlation coefficient of 0.85. Given that the first two velocity potential EOFs are in spatial quadrature, the period of this feature, captured by the first two EOFs, is 40 days. Not only is this result consistent with the spectral analysis of the eddy transient momentum flux, but it is also very close to the MJO period in the atmosphere (Madden and Julian 1971, 1972).

In the UW case, where the prescribed SST is raised by 3 K everywhere, the amplitude of the model's MJO becomes stronger. Consistent with this change, the westerlies over the Tropics also intensify. The deviation of $[\overline{u}]$ for the UW case from that for the control case, shown in Fig. 7b, indicates that $[\overline{u}]$ at the 200-mb level, over the equator, is increased by 2 m s^{-1}. As for the control case, Figs. 11a–c indicate that the transient eddy momentum flux for the UW case is also dominated by zonal wavenumber 1 and a range of periods approxi-

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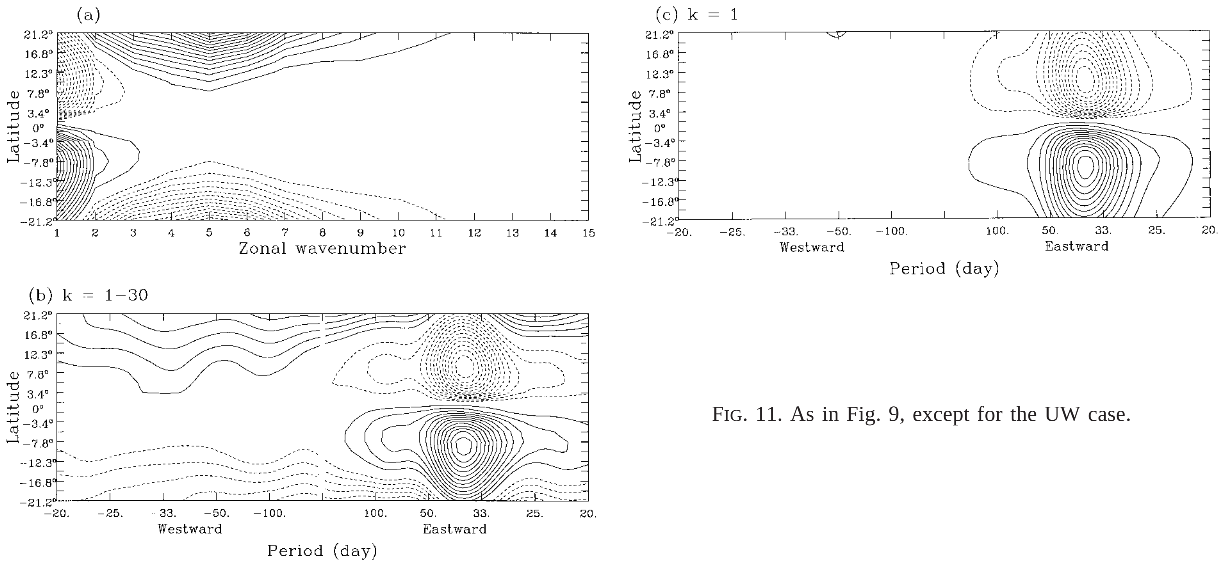

FIG. 11. As in Fig. 9, except for the UW case.

mately between 30 and 70 days, except that the peak period is now 38 days, perhaps due to the increased Doppler shift by the strengthened tropical westerlies. Comparing Figs. 11a–c with 9a–c, one notes for the UW case that the amplitude of the eddy momentum flux by the MJO is increased by a factor of 1.6. Consistent with this result, the velocity potential EOF analysis indicates that sum of the variance of the first two EOFs is 5.66×10^{16} m^4 s^{-2} and 7.61×10^{16} m^4 s^{-2} for the control and UW cases, respectively. In light of climate change and global warming, to the extent that the basic mechanism of the MJO is faithfully represented in this GCM, it is interesting to note that strength of the MJO and the equatorial westerlies increase as the SST increases.

5. Concluding remarks

The aim of this study was to examine whether eddies generated in midlatitudes are a major factor in maintaining the tropical upper-tropospheric easterlies. This is accomplished by examining the decomposition of the transient momentum flux into its eddy and meridional components. It is found that the midlatitude-generated transient eddies do not play an important role in the zonal mean zonal wind budget of the deep Tropics. Instead, this study shows that the intraseasonal (MJO) and intraannual/interannual timescales dominate the transient eddy momentum flux in the deep Tropics. For the interannual timescale transient eddy momentum flux, we suspect that ENSO plays an important role. More importantly, the intraseasonal (MJO), intraannual, and interannual timescale transient eddies each contribute to the acceleration of the equatorial zonal mean zonal wind.

In contrast to the role of the transient eddy momentum fluxes, the momentum flux convergence due to the transient meridional circulation exerts a deceleration of the zonal mean zonal wind in the equatorial upper troposphere. In fact, the zonal momentum budget suggests that it is the transient meridional momentum flux convergence that is the most important factor in maintaining the climatological zonal mean upper-tropospheric easterlies in the Tropics. Because the transient meridional momentum fluxes are almost entirely due to the seasonal cycle of the Hadley cells, this result implies that a nonzero obliquity of the earth is crucial for maintaining the present climate's equatorial easterlies.

In summary, for the intraseasonal, intraannual, and interannual timescales, the transient eddy momentum fluxes dominate the transient meridional momentum fluxes, accelerating the zonal mean zonal winds in the equatorial upper troposphere. However, this acceleration is weaker than the deceleration of the zonal winds due to the seasonal cycle contribution to the transient meridional momentum fluxes. Therefore, the net effect of the all transients is to decelerate the zonal mean zonal winds in the equatorial upper troposphere.

The role of the MJO for the equatorial acceleration is also illuminated with two idealized GCM runs. Because the SST distributions and the value of the insolation are fixed in these GCM runs, the amplitude of transients whose time scale is greater than a season is very small, at least in the Tropics. Therefore, in the Tropics, the momentum flux by the transient meridional circulation is essentially nonexistent, and the transient eddy momentum flux is dominated by the intraseasonal timescale MJO, rather than seasonal and interannual timescale fluctuations. Recalling that in the observations the primary contributor to the maintenance of the tropical upper-tropospheric easterlies is the transient meridional momentum flux convergence due to the seasonal cycle of the Hadley cells, consistent with the fact that

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this quantity is essentially absent in these GCM runs, the zonal winds in the tropical upper troposphere are westerly. When the prescribed value of the SST field is uniformly raised in one of the GCM runs, the model's MJO is stronger and accompanies a greater transient eddy momentum flux convergence, resulting in stronger westerlies over the equator.

The analyses in this study shed new light on our understanding of the earth's general circulation in that equatorial westerlies may be *possible* if the MJO becomes stronger and/or if the obliquity of the earth were to decrease by a sufficient amount. The results of this study also imply a potentially serious limitation in the ability of perpetual GCM runs to faithfully represent the atmospheric circulation in the Tropics, as such models are lacking a seasonal cycle of the meridional circulation, which is crucial for maintaining easterlies over the tropical upper troposphere.

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REFERENCES

Edmon, H. J., B. J. Hoskins, and M. E. McIntyre, 1980: Eliassen–Palm cross sections for the troposphere. *J. Atmos. Sci.,* **37,** 2600–2616.

Feldstein, S. B., and I. M. Held, 1989: Barotropic decay of baroclinic waves in a two-layer beta-plane model. *J. Atmos. Sci.,* **46,** 3416–3430.

Hayashi, Y., 1982: Space-time spectral analysis and its application to atmospheric waves. *J. Meteor. Soc. Japan,* **60,** 156–171.

Held, I. M., and A. Y. Hou, 1980: Nonlinear axially symmetric circulations in a nearly inviscid atmosphere. *J. Atmos. Sci.,* **37,** 515–533.

——, and P. J. Phillips, 1987: Linear and nonlinear barotropic decay on the sphere. *J. Atmos. Sci.,* **44,** 200–207.

Hide, R., 1969: Dynamics of the atmospheres of the major planets with an appendix on the viscous boundary layer at the rigid boundary surface of an electrically conducting rotating fluid in the presence of a magnetic field. *J. Atmos. Sci.,* **26,** 841–853.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kiladis, G. N., and H. F. Diaz, 1989: Global climatic anomalies associated with extremes in the Southern Oscillation. *J. Climate,* **2,** 1069–1090.

Knutson, T. R., and K. M. Weickmann, 1987: 30–60-day atmospheric oscillations: Composite life cycles of convection and circulation anomalies. *Mon. Wea. Rev.,* **115,** 1407–1436.

Lindzen, R. S., and A. Y. Hou, 1988: Hadley circulations for zonally averaged heating centered off the equator. *J. Atmos. Sci.,* **45,** 2416–2427.

Madden, R. A., and P. Julian, 1971: Detection of a 40–50 day oscillation in the zonal wind. *J. Atmos. Sci.,* **28,** 702–708.

——, and ——, 1972: Description of global scale circulation cells in the tropics with a 40–50 day period. *J. Atmos. Sci.,* **29,** 1109–1123.

Oort, A. H., and J. P. Peixoto, 1983: Global angular momentum and energy balance requirements from observations. *Advances in Geophysics,* Vol. 25, Academic Press, 355–490.

Peixoto, J. P., and A. H. Oort, 1992: *Physics of Climate.* American Institute of Physics, 520 pp.

Randel, W. J., and I. M. Held, 1991: Phase speed spectra of transient eddy fluxes and critical layer absorption. *J. Atmos. Sci.,* **48,** 688–697.

Saravanan, R., 1993: Equatorial superrotation and maintenance of the general circulation in two-level models. *J. Atmos. Sci.,* **50,** 1211–1227.

Schneider, E. K., 1977: Axially symmetric steady-state models of the basic state for instability and climate studies. Part II: Nonlinear calculations. *J. Atmos. Sci.,* **34,** 280–297.

Simmons, A. J., and B. J. Hoskins, 1978: The life cycles of some nonlinear baroclinic waves. *J. Atmos. Sci.,* **35,** 414–432.

Suarez, M. J., and D. G. Duffy, 1992: Terrestrial superrotation: A bifurcation of the general circulation. *J. Atmos. Sci.,* **49,** 256–269.

Zhangvil, A., and M. Yanai, 1980: Upper tropospheric waves in the tropics. Part I: Dynamical analysis in the wavenumber-frequency domain. *J. Atmos. Sci.,* **37,** 283–298.

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