Interannual Modes of Variability in Atmospheric Angular Momentum

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ABSTRACT

The interannual variability of atmospheric angular momentum over a 26-yr period is studied regionally using monthly analyses of zonal winds derived from the global rawinsonde network. Variations in zonal-mean momentum, filtered to emphasize interannual timescales, exhibit a coherent propagating signal emanating from low latitudes, as identified in other studies using shorter records. Applying extended empirical orthogonal function (EOF) analyses to zonally varying data, the authors isolate a dominant pair of eigenvectors whose principal component time series and spatial patterns are in quadrature with one another, indicating oscillatory behavior. The oscillation described by the two EOFs has a period of about 36 months and is linked posteriori to the time evolution of the El Niño–Southern Oscillation phenomenon. Beginning as an anomaly over the Tropics that extends from the Indian Ocean into the Pacific, the signal is observed to progress eastward and poleward into both hemispheres, leading to a bipolar structure straddling the central tropical Pacific Ocean. A lagged teleconnection analysis between the Pacific centers and remote sectors corroborates the EOF results. The first pair of eigenvectors contributes substantially to the interannual variance in global angular momentum and to the variability of the zonal-mean momentum field at low latitudes. A second pair of eigenvectors, also in quadrature with one another, describes a biennial oscillation related to zonal momentum variability at higher latitudes.

1. Introduction

Low-frequency variability in the atmosphere is associated with hemispheric and global patterns of large-scale flow anomalies and has been the subject of numerous recent studies. A variety of mechanisms has been proposed to account for observed low-frequency teleconnections in the global atmosphere. At interannual timescales, potential mechanisms to explain such behavior include large-scale instabilities (Frederiksen 1983; Simmons et al. 1983), zonal-mean flow variations (Nigam and Lindzen 1989; Kang 1990), anomalous diabatic forcing (Hoskins and Karoly 1981; Navarra 1990), and the atmospheric response to atmosphere–ocean coupling (Philander 1990). Many interannual variations in the atmosphere have been tied to the El Niño–Southern Oscillation phenomenon, whose basic elements involve a major shift of atmospheric mass across the Pacific Ocean and an oscillation in tropical ocean surface temperatures (Rasmusson and Carpenter 1982). Indeed, there are important anomalies in the zonal wind field, over the Pacific Ocean and elsewhere, that occur in association with the ENSO cycle (Arkin 1982).

When zonal winds are weighted according to atmospheric density and distance from the earth’s axis, a measure of the relative angular momentum of the atmosphere is formed. Integrated over the globe, atmospheric angular momentum (AAM) represents a single geophysical parameter that measures the intensity of the zonal circulation and whose variations are strongly linked to small, but measurable, changes in the earth’s rotation rate. Because of its fundamental importance to earth system dynamics, AAM is presently being operationally monitored at a special data center (Salstein et al. 1993). Although variations in AAM are dominated by seasonal scales, subseasonal and interannual signals are also present and of considerable interest (Hide and Dickey 1991; Eubanks 1993; Rosen 1993).

Interannual variations in AAM and in the length of day (I.o.d.) are well correlated with the occurrence of ENSO events, based on historical astronomical records (Jordi et al. 1994 and references therein). Values of I.o.d. are typically higher during winters following notable warm events, during the “mature phase” of ENSO (as defined by Rasmusson and Carpenter 1982). When the meridional structure of interannual AAM variations is studied, the latitudinal origin of such wind-based anomalies becomes more apparent. In particular, the structure of AAM within zonal belts reveals strong interannual variability across the entire tropical and subtropical region of each hemisphere (Rosen et al. 1991). The spatial and temporal evolution of such

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fields and how they relate to the different phases of the ENSO cycle are two questions addressed here.

Interannual variations in zonal-mean zonal wind and momentum appear to exhibit a tendency to propagate from the Tropics to high latitudes in each hemisphere (Yasunari 1987; Dickey et al. 1992, hereafter DMH). Using global operational zonal wind analyses produced by the National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center) and integrated into a set of 46 equal-area latitude belts (Rosen and Salstein 1983), DMH discovered an alternating series of poleward propagating positive and negative zonal-mean anomalies during the period beginning in 1976. Interestingly, DMH also found that the interannual variations tend to occur primarily on two distinct timescales—a low-frequency component having a period near 4.2 years and a higher-frequency component with a 2.4-yr timescale.

Regional circulation structures associated with extremes in global AAM were studied by Kang and Lau (1994). They found that, on interannual timescales, the dominant mode of variability consists of superrotational zonal flow at low latitudes with twin anticyclones straddling the equator over the central Pacific. Because of the zonally symmetric structure of the mode, it projects strongly upon time series of global AAM. Similar structures have also been identified in the studies of Mo and Kousky (1993), Lau et al. (1994), and Hsu (1994). Here we bridge a gap between these studies, which examined the stationary regional anomaly structure, and DMH, who documented meridional propagation of zonal-mean anomalies, by identifying the regional patterns of time variation associated with this propagation. To the best of our knowledge, the regional evolution associated with observed global AAM variations has not been previously examined.

We use a rawinsonde-based global dataset extending back to the early 1960s, prior to the advent of global operational analyses, to (a) study the reproducibility of DMH’s results in earlier years and (b) construct a larger database for eigenvector analysis of associated anomaly patterns. Atmospheric variables from this station-based set, including zonal winds, were interpolated to a regular grid using distance-based and shape fitting corrections to an initial guess field (Oort 1983). From these data the global patterns that are associated with the meridional propagation of zonal-mean anomalies were identified. In section 2, the basic characteristics of the rawinsonde dataset and the filtering procedure used to study interannual variability are outlined, and the zonal-mean results are compared with those of DMH. Section 3 describes the primary spatial pattern of variability identified from extended empirical orthogonal function (EEOF) and teleconnection analyses and examines how this pattern contributes to variations in zonal-mean AAM. In section 4 a secondary pattern of interannual variability with a biennial time-scale is discussed. We summarize and present conclusions in section 5.

2. Rawinsonde dataset and preliminary analyses

The basic dataset is derived from an extensive collection of monthly mean values of rawinsonde station observations produced by A. Oort of the Geophysical Fluid Dynamics Laboratory/National Oceanic and Atmospheric Administration (NOAA) (Peixoto and Oort 1992). The station data have been fitted to a regular global grid for a 26-yr period starting in May 1963, using an objective analysis scheme designed for this purpose (Oort 1983). Although the configuration of rawinsonde stations is spatially uneven and there are considerable data gaps over portions of the Tropics, the Southern Hemisphere, and oceanic regions, the distribution is relatively stable during the period and the objective analysis scheme attempts to reduce the effects of these gaps (Oort 1983). We consider the analysis fields derived from these stations to be suitable for studying a number of planetary-scale aspects of interannual variability. The grid resolution of the analyzed station data is $2.5^\circ \times 5^\circ$ in latitude and longitude, respectively, and global grids of zonal wind at 11 pressure levels form the basis for calculating AAM.

Relative AAM was calculated as an integral over a volume, either within a local region or over the whole globe, according to the following:

$$M = \frac{a^3}{g} \iiint u \cos^2 \phi \, d\phi \, d\lambda \, dp,$$

where $a$ is the mean radius of the earth; $g$ acceleration due to gravity; $u$ zonal wind; and $\phi$, $\lambda$, and $p$ latitude, longitude, and pressure, respectively. The pressure integral is taken from 100 to 1000 hPa. Because of the strong weighting by axial distance in (1), low-latitude regions contribute strongly to globally integrated values of $M$. The time series of monthly $M$ integrated over the globe is plotted as the thin line in Fig. 1. We note that the curve contains a prominent seasonal signal, reaching peak values during Northern Hemispheric winter, in addition to significant smaller-amplitude variations on longer interannual timescales. Further aspects of the global momentum evolution are explored after discussions of regional momentum features.

In DMH, interannual variations of zonally integrated values of $M$ are found to propagate from equatorial regions to high latitudes. Two specific interannual timescales related to this behavior were identified by DMH (also see Keppenne and Ghil 1992): one just over 4 years and another at a quasi-biennial timescale. To isolate behavior over a similar range of timescales, a Fourier filter was here applied to 26 years of the rawinsonde-based dataset. The input AAM time series at each grid point consists of 312 data points for the months ranging from January 1964 to December 1989. After transforming each time series into the spectral
Fig. 1. Time series of monthly global atmospheric angular momentum between 100 and 1000 hPa derived from the rawinsonde data and NCEP operational analyses. The thin solid line is the unfiltered rawinsonde data with the long-term mean removed. The thick solid and dashed lines are the Fourier-filtered rawinsonde and NCEP analyses, respectively. See text for details of the Fourier filter.

domain, we multiply each frequency coefficient by the weighting factors displayed in Fig. 2 before returning to the time domain. The Fourier filter thus retains oscillation periods between approximately 17 and 80 months. The weighting factors were tapered from 0 to 1 to minimize the effect of ringing at the cutoff frequencies (e.g., Press et al. 1992). Because the input data are not necessarily zero at, or periodic with respect to, the endpoints, there exists the possibility of spurious responses near the beginning and end of the output time series. We have tested this possibility and found that our results are not sensitive to inclusion of data near endpoints. Thus, we include the entire filtered data record for input to the subsequent EEOF analyses.

The Fourier filter effectively eliminates both decadal and intraseasonal timescale variations, as is evident from the filtered time series (thick solid curve) in Fig. 1. The thick dashed curve shows the same Fourier-filtered quantity derived from NCEP-based analyses since these data became available in the latter half of the 1970s. The rawinsonde and NCEP data generally show good agreement during their period of overlap. Thus, we are reasonably confident that both of these datasets are able to capture similar large-amplitude, low-frequency behavior, and we regard the rawinsonde dataset as suitable for studying interannual angular momentum variability.

Time series of monthly rawinsonde-based values of \( M \) were calculated for the set of 46 equal-area latitude belts spanning the globe, as defined by Rosen and Salstein (1983). A time–latitude plot of the Fourier-filtered and zonal-mean belt data is shown in Fig. 3 (short tick marks along the latitude axis indicate the boundaries of the 46 latitude belts). The alternating patterns of positive and negative anomalies in this figure duplicate many of the characteristics shown in DMH. The chevron-shaped anomaly patterns indicate a fairly regular progression of positive and negative momentum anomalies from low to higher latitudes in both hemispheres. Poleward propagation is evident throughout the data record, particularly during the late 1960s and early 1970s, prior to the advent of the NCEP operational dataset. The poleward progression becomes less coherent at high latitudes where there is evidence of both poleward and equatorward propagation. Interestingly, and in contrast to DMH, the anomaly pattern associated with the strong 1982–83 ENSO event exhibits a weaker propagation in the filtered rawinsonde data. This difference will be discussed later.

The asterisks in Fig. 3 indicate the mature phase of major ENSO warm events (e.g., Rasmusson and Carpenter 1982) and correspond to the time when sea surface temperature anomalies in the central Pacific reach maximum values (e.g., Barnett 1991). The meridional
propagation of positive AAM anomalies from the Tropics tends to be linked with the warm phase of ENSO. During the mature phase of ENSO, there are positive maxima located over the subtropics. It should be noted, however, that not every positive AAM anomaly is associated with an ENSO event, although those that develop strong midlatitude anomalies do appear to be. To isolate regional patterns of variation related to these meridionally propagating signals, we use the set of rawinsonde-based analyses during this multidecadal period.

Using the station-based analyses, monthly values of $M$ were calculated using (1) over a grid of 1104 sectors, which span 15° of longitude and whose meridional limits are discussed above. The 26-yr time average of $M$ in these sectors is contoured in Fig. 4a, indicating weak easterly momentum at low latitudes and large values of westerly momentum at middle and high latitudes. Particularly strong westerly maxima are found in the jet cores over eastern North America, eastern Asia, and within a band extending across midlatitudes in the Southern Hemisphere. The standard deviation of $M$, containing variations on all timescales from monthly to decadal, is given in Fig. 4b. Centers of strong variability generally match the local maxima in the time-mean $M$. To isolate variability at interannual timescales, the sector time series are Fourier filtered, as described above. The local standard deviation of the Fourier-filtered data is displayed in Fig. 4c. As expected, variance is reduced over most locations and new local maxima become evident. The interannual variability is particularly strong over the North Atlantic, over the eastern continental regions of the Northern Hemisphere, and in a pair of centers located over the subtropical central Pacific Ocean.

3. Regional patterns of interannual variability: Modes 1 and 2

a. Eigenvector analysis of station momentum data

Given that the zonal-mean momentum data suggest a coherent poleward propagation in time, we are interested in deducing the regional behavior of this phenom-
Mean AAM (5/63–12/89)

\[(10^{22} \text{ kg m}^2 \text{ s}^{-1})\]

Standard Deviation of Unfiltered AAM (5/63–12/89)

\[(10^{22} \text{ kg m}^2 \text{ s}^{-1})\]

Fig. 4. Regional statistics of monthly atmospheric angular momentum calculated for 1104 equal-area sectors. (a) Long-term mean averaged from May 1963 to December 1989. Contour interval is $5 \times 10^{22}$ kg m$^2$ s$^{-1}$, and values greater than $10 \times 10^{22}$ kg m$^2$ s$^{-1}$ are shaded. (b) Standard deviation for unfiltered data between May 1963 and December 1989. Contour interval is $3 \times 10^{22}$ kg m$^2$ s$^{-1}$, and values greater than $6 \times 10^{22}$ kg m$^2$ s$^{-1}$ are shaded. (c) Standard deviation of Fourier-filtered data between January 1964 and December 1989. Contour interval is $0.5 \times 10^{22}$ kg m$^2$ s$^{-1}$, and values greater than $1.5 \times 10^{22}$ kg m$^2$ s$^{-1}$ are shaded.
Standard Deviation of Filtered AAM (1/64–12/89) 
\(10^{22} \text{ kg m}^2 \text{ s}^{-1}\)

Fig. 4. (Continued)

The basic data input to the EEOF analysis are assembled from the global grids of \(M\), each grid consisting of 1104 spatial sector elements. Information about the temporal evolution is introduced into the state vectors by appending to each global grid similar grids taken from neighboring time periods. For example, suppose that at time \(t\) the global grid of \(M\) is given by the state vector \(\mathbf{M}(t)\). In the EEOF analysis, a new state vector is formed by supplementing \(\mathbf{M}(t)\) with additional grids sampled at times \(t + L, t + 2L, \ldots, t + (n - 1)L\), where \(L\) is the time lag interval between samples and \(n - 1\) the number of additional grids added. The new vector has the form \(\mathbf{M}_g(t) = [\mathbf{M}(t), \mathbf{M}(t + L), \mathbf{M}(t + 2L), \ldots, \mathbf{M}(t + (n - 1)L)]\) and consists of 1104 \(\times\) \(n\) data elements. Using standard matrix techniques, the covariance matrix \(\mathbf{M}_g^T(\mathbf{M}_g)^T\) is then diagonalized, leading to eigenvectors having dimensions 1104 \(\times\) \(n\). The resulting sequence of \(n\) spatial fields represents the space–time evolution associated with each eigenvector. The principal components of each eigenvector are determined by projecting the eigenvector onto the basic input data.

The constants \(L\) and \(n\) were chosen to resolve and span the period of the primary propagating phenomenon depicted in Fig. 3. A lag interval of 3 months adequately resolves the evolution of this phenomenon. Choosing \(L\) to be 3 months, we first selected \(n = 13\) lags to allow timescales of \(\approx 6.5\) years (half-oscillation of 39 months) to be captured. The 13 grids are grouped together to form an individual member of the ensemble that is input into the EEOF analysis. With these values for \(L\) and \(n\), a primary oscillation with a period of about 36 months emerged from the EEOF analysis. Because the 13 lags produce an unneeded repetition of the oscillatory behavior within the EEOF, involving an excessive truncation of the data record, we repeated the EEOF analysis for \(L = 3\) months, but with \(n = 7\) lags. In this experiment, for time \(t\) the input data consist of seven grids sampled at times \(t, t + 3, t + 6, t + 9, t + 12, t + 15,\) and \(t + 18\) mo, capable of resolving periods up to 42 months. The primary oscillation resulting from the second experiment, which is displayed here, is nearly identical to that obtained from the analysis with \(n = 13\).

Modes 1 and 2 of the EEOF analysis explain 18.2% and 17.1%, respectively, of the regional filtered vari-
ance displayed in Fig. 4c. Their respective principal component time series, displayed in Fig. 5, have a pronounced lag correlation (0.83), with mode 1 lagging mode 2 by 9 months. Thus, the two time series exhibit a quadrature relationship, indicating a coherent oscillation with a basic period of approximately 36 months. The principal component time series also have a longer-term modulation, suggesting that modes 1 and 2 describe an episodic phenomenon. In particular, we note the timing of the five major maxima in the mode 1 time series of Fig. 5, which are approximately contemporary with the mature phase of particular ENSO events (also, compare this to the "full" Southern Oscillation Index in Fig. 4 of DMH). The relationship is incidental, as our analyses presume no knowledge of ENSO.

The eigenvector maps from either mode can be used to represent the temporal sequence of geographical anomaly patterns associated with the oscillation. Because mode 2 is oriented in such a way that its first lag coincides with the phase of anomaly intensification along the equator, we choose to display its sequence in Fig. 6. For reference, the anomaly pattern in Fig. 6c, corresponding approximately to that associated with the mature phase of ENSO, is denoted with a "base" time $T_0$. The prior two time periods, shown in Figs. 6a and 6b, are denoted $T_0 - 6$ and $T_0 - 3$, respectively, and the maps following $T_0$ are denoted $T_0 + 6$, $T_0 + 3$, and $T_0 + 9$ in Figs. 6d, 6e, and 6f, respectively. The following map, $T_0 + 12$, continues the cycle into the opposite phase of the oscillation. The sequence of maps in Fig. 6 illustrates that the oscillation is characterized by a half-period of about 18 months (e.g., contrast Figs. 6a and 6b). As stated above, the map sequence for mode 1 is nearly identical to that in Fig. 6 but is offset by 9 months.

The progression of the oscillation can be described as follows. Six months prior to the mature phase of the ENSO ($T_0 - 6$), a broad band of weakly positive momentum anomalies is found at tropical latitudes, with local maxima over the central Pacific, Indonesia, and South America. Three months later, positive anomalies extend over practically the entire Tropics and subpolar regions, with two strong positive centers located over the subtropical Pacific Ocean, colocated with the regions of strong variability in Fig. 4c. Between $T_0 - 3$ and $T_0$, the positive anomalies along the equator begin to weaken at some longitudes, while those within distinct zonally oriented bands in the subpolar intensify. The restructuring of the anomaly field results in an effective poleward propagation of zonal momentum. At $T_0$ the bipolar pattern over the Pacific nears its greatest mag-

![EEOF Time Coefficients - Modes 1 and 2](image)

**Fig. 5.** Principal component time series for modes 1 (solid line) and 2 (dashed line) of the EEOF analysis described in the text. The two time series exhibit a 9-month lag correlation of 0.83 (mode 2 leads mode 1). Asterisks indicate the timing of the mature phase of major ENSO warm events.
magnitude, similar to features found by Arkin (1982) in a stationary eigenvector analysis of subtropical wind anomalies. This correspondence with Arkin’s results provides added confidence in the robustness of our results and in the utility of the dataset used here. The structural evolution at high latitudes is less coherent during this time, although there is some evidence of eastward and, to a lesser extent, equatorward propagation of momentum anomalies at high latitudes in the Northern Hemisphere.

After \( T_0 \) the equatorial anomalies continue to decrease, further isolating positive anomalies toward

Fig. 6. Global maps of the oscillation described by the first mode pair in an EEOF analysis of global patterns of bandpass-filtered atmospheric angular momentum. The lags of mode 2 are used to depict the regional anomaly evolution that typically occurs in relation to the mature phase of ENSO (lag \( T_0 \)). Lags range from (a) 6 months prior to \( T_0 \), to (g) 12 months afterward. The contour interval is 0.75 (nondimensional). Values greater (less) than 0.75 (−0.75) are lightly (darkly) shaded. Note that (g) resembles (a) but with the sign reversed.
higher latitudes. This net poleward progression of zonal momentum anomalies is consistent with Fig. 3 and with the zonal-mean analyses of DMH. At $T_0 + 3$ the primary positive anomalies in the Northern Hemisphere have also spread eastward, and the bipolar pattern over the Pacific weakens thereafter. Between $T_0 + 3$ and $T_0 + 9$, the positive anomalies retract toward higher latitudes in both hemispheres, as negative anomalies arise across the Tropics. Thereafter, there is a transition into the opposite phase of the oscillation (note that $T_0 + 12$ is similar to $T_0 - 6$ except with the sign reversed). The sequence of maps in Fig. 6 completely describes one-half of the period of oscillation characterized by modes 1 and 2.

Although modes 1 and 2 contribute only 35% to the total regional variance, they account for 90% of the variance in global-mean Fourier-filtered $M$. This is demonstrated in Fig. 7 by comparing the global $M$ due to modes 1 and 2 (dashed curve) with the total filtered variation in $M$ (solid curve). The dashed curve is that portion of the variation in global $M$ explained by the first two eigenmodes. This is obtained by first multiplying the principal component of each mode by its corresponding eigenvector maps to reconstruct a portion of the data. The data are then averaged over the seven lags related to each epoch and integrated according to (1) (for more detail see section 3c). There is an excellent correspondence between the reconstructed time series and the total filtered $M$, partly because the anomaly patterns of modes 1 and 2 consist mainly of perturbations having one sign over much of the globe. Thus, the resulting spatial integral of $M$ based on these modes makes a substantial contribution to time variations in global $M$.

The Pacific bipolar pattern in Fig. 6 is consistent with results of recent studies examining the relationship between tropical heating and global circulation or temperature on interannual timescales (Mo and Kousky 1993; Hsu 1994; Yulaeva and Wallace 1994) and those studying fundamental modes of variability in upper-tropospheric flow (Lau et al. 1994). At upper levels, the structures identified exhibit a superrotational flow throughout most of the Tropics, except over the central Pacific where twin anticyclones straddle the equator (Fig. 1a of Lau et al. 1994). Lau et al. find that the tropical anomaly patterns exhibit significant antisymmetry between the upper and lower troposphere, with a broad region of surface easterlies over the Eastern Hemisphere and surface westerlies extending over the central and eastern Pacific. The main perturbation structure is confined to the Tropics and Pacific subtropical regions.

![Global Filtered AAM](image)

**Fig. 7.** Time series of Fourier-filtered global atmospheric angular momentum derived from the rawinsonde data. The solid line is the total filtered time series (as in Fig. 1), and the dashed line is the portion of the total global variability explained by modes 1 and 2 of the EEOF analysis.
An exact correspondence between the propagating anomaly structures of our study and the results of the studies noted above is not expected. First of all, the analyses of the previous studies have identified static (nonpropagating) anomaly patterns that represent an amalgamation of the moving oscillations identified here. Secondly, our analyses focus on interannual variations in vertically integrated angular momentum, as opposed to variations in streamfunction or diabatic heating. Nonetheless, a remarkable correspondence is found, suggesting that EOFs 1 and 2 in our analyses are related to the time evolution of an important fundamental mode of interannual variability in the global atmosphere. It is noted that static anomaly patterns similar to those identified by Mo and Kousky (1993) and Lau et al. (1994) are reproduced by Kang and Lau (1994) when they relate time variations in global $M$ to streamfunction anomalies. This provides further evidence of the strong relationship between modes 1 and 2 of our analysis and variations in global $M$. The regional anomaly evolution described by modes 1 and 2 has been noted in connection with ENSO evolution. Wang (1992) describes the motions of ENSO features from the Indian Ocean eastward across the Maritime Continent to the tropical Pacific. The composite analyses of Yasunari (1987) capture similar aspects of the structural evolution over the tropical and subtropical Pacific. Note, however, that unlike Yasunari (1987) our analyses are not based on indices derived from ENSO parameters.

Evidence is emerging that ENSO is a multiple timescale phenomenon (Rasmussen et al. 1990; Barnett 1991). Classic studies of ENSO describe the evolution of individual events through a life cycle of approximately 2–3 years (e.g., Rasmussen and Carpenter 1982) and note that most cases are observed to be phase locked to the annual cycle. In addition, ENSO typically recurs on a longer timescale of 3–7 years (e.g., Barnett 1991). The 36-month timescale of eigenvectors 1 and 2 agrees quite well with the shorter timescale, corresponding to the life cycle of ENSO. As noted earlier, the principal component time series in Fig. 5 also indicate a longer-term modulation that appears linked to the occurrence of ENSO events. Within the spectral window of our time filter, the timescale of the oscillation is automatically selected by the EOF analyses and is insensitive to the precise nature of the filter applied. Our investigation reproduces notable aspects of the temporal and spatial evolution observed in independent studies relying on ENSO-based parameters.

b. Teleconnection analysis

In light of the potential difficulties in interpreting EOF analyses discussed by Chen and Harr (1993), it is prudent to test the robustness of the relationships found using EOFs by performing a parallel teleconnection analysis. To do so, lag correlations are calculated between the gridded angular momentum anomalies and the anomalies at particular base points. The base points were chosen to be the centers of action in the EEOF patterns described above, specifically the subtropical centers over the central Pacific. A high correlation at a negative time lag indicates the existence of a precursor anomaly field forming prior to the occurrence of strong anomalies at the base point. Conversely, a correlation at positive lag indicates that the signal at the base point leads a subsequent regional anomaly elsewhere. Unlike EOF analyses, teleconnections do not provide information on perturbation magnitudes. Thus, in comparing the teleconnection results to the previous EOFs we focus on studying the basic correlation patterns without regard to the details of the correlation magnitudes.

To examine the consistency between the one-point teleconnection analyses and the EOF analyses, results obtained using a base point centered in the South Pacific Ocean (26°S, 150°W) are discussed. The maps in Fig. 8 are the teleconnection patterns for lags ranging from −6 months to +12 months, which correspond to the EOF lags displayed in Fig. 6 and provide for a direct comparison between the two analyses. A tropical precursor exists 6 months prior to the signal in the subtropical South Pacific, with particularly strong positive features over Indonesia, Hawaii, and South America. After 3 months, the correlation pattern encompasses much of the subtropics, with two pronounced centers straddling the equatorial Pacific (Fig. 8b). Thereafter, the region of positive correlations moves eastward while retracting poleward, eventually leading to the formation of a pattern of opposite sign at lag +12. The pattern evolution closely resembles that found in Fig. 6, both in the Tropics and at higher latitudes. Very similar results are obtained for base points in the Northern Hemisphere (not shown).

The teleconnection analyses thus provide strong support for our interpretation of the EOF analyses. Both identify a robust eastward and effective poleward progression of angular momentum anomalies originating in the Tropics. The oscillation exhibits a period of approximately 36 months. Finally, we note that because the base points chosen correspond to local maxima in the standard deviation of AAM (cf. Fig. 4c), the teleconnection analysis is likely identifying a fundamental interannual oscillation of AAM.

c. Reconstruction of zonal-mean patterns

To illustrate how eigenvectors 1 and 2 contribute to the overall meridional propagation of zonal momentum, the zonal-mean anomaly patterns contributed by this pair of eigenmodes are reconstructed. This approach is different from that of DMH, who decomposed zonal-mean data purely on the basis of time filtering. Our method consists of first multiplying each eigenvector by its respective principal component time se-
Fig. 8. Global maps of the lag correlation between bandpass-filtered angular momentum at sector 150°W, 26°S and all other sectors. The lags range in 3-month intervals from (a) −6 months to (g) +12 months where lag 0 corresponds to T_0 in Fig. 6. The contour interval is 0.15, and correlations greater (less) than 0.30 (−0.30) are lightly (darkerly) shaded.

ries, which then leads to n anomaly maps (where n is the number of lags for each eigenmode, see section 3a) for each mode at every time step. At each time step, all the n relevant anomaly maps found at nearby time steps are then averaged. Finally, each average anomaly map is zonally integrated at each time step, and then the results for the two modes are added. [See Fraedrich et al. (1993) for another example of using EEOFs to reconstruct time series data.] The combined result for modes 1 and 2 is displayed in Fig. 9, which can be directly compared to the total Fourier-filtered zonal-mean data in Fig. 3.

The momentum evolution reconstructed from the mode pair (1,2) clearly demonstrates the 36-month pe-
period of the oscillation. A long-term modulation of the oscillation is also noted in which the largest positive amplitudes tend to occur during prominent ENSO episodes. During each cycle of the oscillation, there is a notable meridional propagation of momentum anomalies from the equator through the subtropics to the mid-latitudes. This is consistent with the net poleward progression of regional momentum anomalies noted earlier in the structural evolution of the mode pair (Fig. 6). Compared with Fig. 3, this mode pair captures much of the observed meridional propagation at low latitudes. Indeed, modes 1 and 2 account for 54% of the observed variability in zonal momentum. At high latitudes modes 1 and 2 capture less of the observed variability, particularly in the Northern Hemisphere where very irregular behavior is found in the observed evolution. Although there is evidence of equatorward propagation for modes 1 and 2 at these latitudes, the anomaly magnitudes are relatively weak.

The close relationship between the poleward propagating positive anomalies and major ENSO warm events includes the 1982–83 El Niño, which is characterized by poleward propagation in the mode pair (1,2) reconstruction, in contrast to the observed fields (Fig. 3), which exhibit more of a standing pattern. Separate analyses show that when the results of Fig. 3 are reproduced for only the Pacific sector (not shown), such propagation indeed occurs. During the strong and extraordinary 1982–83 El Niño there is apparent significant compensating behavior outside the Pacific region that helps produce the standing oscillation found in the observed zonal-mean evolution at low latitudes. Although interesting, this possibility is not investigated here, as such idiosyncratic behavior is regarded as being beyond the scope of the present study.

4. Secondary modes of variability

a. Variability at high latitudes: Modes 3 and 4

Because only about 35% of the regional variability of filtered angular momentum is explained by modes 1 and 2, higher-order modes are required to account for the remaining variability. Modes 3 and 4 of the EEOF analysis also exhibit a quadrature relationship with one another, and they describe an oscillation having a period of 24 months. The principal component time series for modes 3 and 4 are plotted in Fig. 10. The time series for mode 4 lags that of mode 3 by 6 months, with a lag correlation of 0.83. Unlike the case of modes 1 and 2, there is no obvious relationship between these time series and major ENSO events. Together, modes 3 and 4 account for 16% of the total regional variance. Although the number of lags and the lag interval were chosen to reveal the primary oscillation described by modes 1 and 2, these parameters are also suitable for describing the behavior of modes 3 and 4. Five lags of mode 3 are used to depict the oscillation pattern in Fig. 11. Modes 3 and 4 have relatively more variability at middle and high latitudes than modes 1 and 2. At all lags robust anomalies of opposite sign are found in the extratropics of each hemisphere.

The primary regional anomalies are replaced by anomalies of the opposite sign between lag zero and lag +12. Thus, the five maps succinctly represent one half-period of the oscillation, illustrating the 24-month timescale. The evolution exhibits somewhat less coherence than found for the first two modes. There is some indication of poleward motion of anomaly centers over the Northern Hemisphere between lag zero and lag +12, and there is weaker evidence of poleward propagation in anomalies over the Southern Hemispheric subtropics. At high latitudes in the Southern Hemisphere there appears to be a standing oscillation in zonal momentum. The features of interest are of smaller scale than in modes 1 and 2, and unlike in modes 1 and 2, the global integral of modes 3 and 4 is small, as there is much cancellation between regional anomaly centers of opposite sign. Thus, these modes do not explain much of the variability in global momentum, but rather explain important regional (and
zonal) variability. Recall that 90% of the variance in global momentum is explained by modes 1 and 2.

The 24-month timescale is shorter than that of the atmospheric quasi-biennial (QB) oscillation, a dominant period for interannual variations in both the extratropical and equatorial stratosphere (Holton and Tan 1980). Because $M$ is integrated through the depth of the troposphere and only up to 100 hPa in the lower stratosphere, it is more likely that these modes may be associated with the extratropical QB oscillation, which tends to have a stronger reflection below 100 hPa (Dunkerton and Baldwin 1991). This is consistent with the observation that most of the regional variability associated with modes 3 and 4 is confined to higher latitudes. Modes 3 and 4 may also have some relation to the QB zonal component isolated by DMH with the aid of an 18–35-month Fourier filter. In any case, as discussed above, modes 3 and 4 display no apparent relationship with ENSO. In the next section we examine how modes 3 and 4 contribute to the meridional structure of zonal momentum anomalies.

b. Reconstruction of zonal-mean patterns from modes 3 and 4

The behavior of the zonal-mean data reconstructed from mode pair (3,4) is displayed in Fig. 12. Modes 3 and 4 contribute about 28% to the total zonal-mean momentum variability. Successive oscillatory episodes occur on a biennial timescale but exhibit weaker amplitudes than modes 1 and 2. The primary anomalies are found at higher latitudes where the mode pair (1,2) exhibits weaker amplitudes. Poleward propagation is observed at these latitudes, particularly in the Northern Hemisphere, similar to DMH’s findings for their QB filtered data. At very high latitudes in the Southern Hemisphere there is an alternation between anomalies of opposite sign, consistent with the regional standing oscillation noted in Fig. 11. Accordingly, mode pair (3,4) does not appear to be linked to particular phases of ENSO, as noted in the time series analyses of Fig. 10. This fact, taken with the observation that much of the variability of this mode pair occurs at mid- to high latitudes, suggests that the behavior described by mode pair (3,4) is likely independent of the tropical Southern Oscillation.

5. Summary

We have isolated fundamental global modes of interannual variability in atmospheric angular momentum from 26 years of global rawinsonde data using extended EOF analyses. The primary oscillation has a period of 36 months, and its phase is strongly linked to the El Niño–Southern Oscillation phenomenon. The oscillation begins with the formation of a broad band
of angular momentum anomalies extending from the Indian Ocean eastward to South America. The anomaly pattern expands to encompass most of the subtropics and Tropics, giving rise to a bipolar structure straddling the central tropical Pacific. Thereafter, the equatorial anomalies weaken and the subtropical maxima intensify, resulting in an effective poleward propagation of zonal momentum anomalies. Lastly, the subtropical anomalies are observed to weaken and propagate eastward while continuing to progress poleward. The regional structure of the primary oscillation was confirmed by teleconnection analyses.

At its largest amplitude, the bipolar structure over the central Pacific closely resembles those identified in earlier studies of stationary anomaly structures (Arkin 1982; Mo and Kousky 1993; Hsu 1994; Kang and Lau 1994; Lau et al. 1994). Here, the regional evolution of this global pattern has been isolated. The primary oscillation accounts for 90% of the time-filtered interannual variability in global atmospheric angular momentum and about 54% of the zonal-mean variability. The time evolution is closely tied to the ENSO cycle, with a distinct poleward propagation of positive zonal momentum anomalies observed during warm events. This association emerges independently, as our analyses do not contain a priori information about the ENSO cycle.

The 36-month period of the oscillation is consistent with the timescale associated with the life cycle of individual ENSO events (Xu and von Storch 1990). A longer-term amplitude modulation likely related to the frequency of ENSO recurrence (Barnett 1991) was also observed. The oscillation's timescale and association (in both time and space) with ENSO suggest that it is likely strongly coupled to oceanic interannual variability. Further study of atmospheric and oceanic data will be necessary to clarify this relationship.

FIG. 11. Global maps of the oscillation described by the second mode pair of the EEOF analysis. The lags of mode 3 are used to depict the regional anomaly evolution that occurs during the oscillation. Lags range in 3-month intervals from (a) zero to (e) +12 months. The contour interval is 0.75 (nondimensional). Values greater (less) than 0.75 (~0.75) are lightly (darkly) shaded.
A biennial oscillation is also identified from our analyses, accounting for under 10% of the variance in global momentum and about 16% of the regional variance. This oscillation is characterized by marked variability at mid- to high latitudes, especially in the Southern Hemisphere. In the Northern Hemisphere, bands of like-signed anomalies progress northward from mid-latitudes, resulting in an effective poleward motion of zonal momentum anomalies to higher latitudes. The strongest signal in the Southern Hemisphere is a standing oscillation at high latitudes. We speculate that our biennial oscillation may be related to the extratropical QB oscillation, which is observed to extend into the upper troposphere (Dunkerton and Baldwin 1991). Further analyses will be necessary to test the robustness of the biennial oscillation, however, as its characteristics were not confirmed here in independent analyses.

The zonal-mean anomaly evolution associated with the two oscillations identified in our modal analysis resembles the behavior in the time-filtered analyses of DMH for the two studies' overlap period. More generally, however, there is not an exact correspondence between our modes and DMH's two components, particularly in the extratropics. Whereas each of DMH's components exhibits both poleward and equatorward anomaly progression in the Northern Hemisphere extratropics, the modal evolutions in our Figs. 9 and 12 do not; in middle to high latitudes of the Northern Hemisphere the primary mode is restricted to equatorward progression and the biennial mode to poleward progression. Comparisons between the two studies are complicated by the fact that the timescale for our primary oscillation (36 months) lies near the boundary of the two frequency bands isolated by DMH (18–35 months and 32–88 months). Also, our primary oscillation experiences a longer timescale amplitude modulation related to the recurrence time of ENSO. Therefore, it is likely that this mode would project upon both frequency bands considered by DMH. In addition, distinctions may result from the different epochs considered by the two studies. The earlier period incorporated here spans an apparent interdecadal change in sea surface temperatures that may influence the behavior of ENSO-related variations (Wang 1995), and our primary oscillation is largely influenced by behavior in the first half of the data record.

The correspondence between the bipolar structures found in our study and in previous investigations of time-invariant anomaly structures illustrates the utility of the rawinsonde dataset used. Nonetheless, future studies will benefit substantially from the availability of long-term reanalyses currently being produced at the NCEP (Kalnay and Jenne 1991) and elsewhere. These data will be invaluable in extending the present analyses to obtain a more complete picture of interannual variability in the global circulation. The framework of the generalized Eliassen–Palm relation will be useful in investigating the dynamic aspects of interannual variations in AAM across the globe. The long-term reanalyses will provide a key resource in assessing regional sources of interannual wave activity.

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