Are EOF-based indices of the Madden-Julian Oscillation relevant to its role in ENSO?

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ABSTRACT

Although several recent El Niño events have seen the occurrence of strong intraseasonal winds associated with the Madden-Julian Oscillation (MJO), the usual indices of interannual variability due to the MJO (typically based on EOF modes) are uncorrelated with measures of the ENSO cycle. The reason for this lack of correlation is investigated by comparing two different types of MJO indices, one constructed from the lowest quadrature pair of modes in an SVD decomposition of intraseasonal OLR and another that locally determines the occurrence of large-scale, eastward-propagating intraseasonal signatures. The SVD description produces a zonally-fixed envelope extending from the Indian Ocean to the west Pacific, within which MJO events propagate eastward. The envelope is fixed because a single quadrature mode pair does not represent both intraseasonal propagation and east-west wandering of the region of MJO activity. Interannual variability in this representation consists solely of changes in the magnitude of intraseasonal fluctuations. This variability is uncorrelated with the Southern Oscillation Index, as others have shown. The locally-determined index, on the other hand, shows that interannual zonal meandering of the envelope of MJO activity is well-correlated with the ENSO cycle. This aspect of MJO interannual variation must not be excluded in analyses of the possible MJO-ENSO connection.

1. Introduction

The regular occurrence of strong intraseasonal oscillations during the onset of El Niño events (Luther et al 1983; Kessler and McPhaden 1995; Verbickas 1998; McPhaden 1999) has sparked interest in the possibility of a physical connection between the two frequencies (Lau and Chan 1988; Weickmann 1991; Kessler et al 1995; Fink and Speth 1997; Moore and Kleeman 1998; Slingo et al 1999; Hendon et al 1999; McPhaden and Yu 1999; Kessler and Kleeman 2000). Nevertheless, demonstrating such a connection has been difficult and controversial because indices of the most prominent intraseasonal signal, the Madden-Julian Oscillation (MJO; Madden and Julian 1994) suggest that the MJO is not related to the ENSO cycle (Slingo et al 1999; Hendon et al 1999).

A common method of defining the MJO has been based on eigenvector representations of band-passed variability (e.g., Lau and Chan 1988; Zhang and Hendon 1997; Maloney and Hartmann 1998; among many others). Typically, a field which can be tropical zonal wind at various levels or outgoing longwave radiation (OLR; a measure of tropical deep convection) is bandpassed to intraseasonal frequencies (periods of roughly 30-90 days), then decomposed in empirical orthogonal functions (EOFs) of some kind. The result is pairs of modes in quadrature that, combined, demonstrate a large-scale eastward-propagating signal. The temporal coefficients of the EOF modes can be used to create a low-freqency index of MJO activity (Slingo et al 1999) or to construct a “composite event” (Shinoda et al 1998; Maloney and Hartmann 1998). This general technique is robust in the sense that it is not particularly dependent on the variable studied, or the details of the bandpass, or the type of EOF analysis employed. Such an analysis has the advantage that it consistently identifies an intraseasonal signal that can be described as tropically-trapped with largest amplitude over the Indian and west Pacific Oceans, and eastward propagating with low zonal wavenumber and speeds of a few m s^{-1}. This type of representation has come to be accepted in the atmospheric community as defining the MJO.

The conundrum for those wishing to understand the relation between the MJO and the onset of El Niño is that on the one hand recent El Niños have seen a tantalizing set of prominent intraseasonal events, but on the other hand the interannual time series that emerge from the EOF modal description are uncorrelated with the Southern Oscillation Index (SOI) or other measures of the ENSO cycle. The purpose of the present note is to examine reasons for this discrepancy and determine the degree to which a EOF description is appropriate for resolving the connection between the MJO and El Niño.

Section 2 describes the data used and Section 3 explains the construction of MJO indices that conform to the usual type, and also a new type of index that has an important advantage in evaluating the relation between the MJO and El Niño. Section 4 compares the results of the different indices, and Section 5 draws conclusions.

2. Data

Pentad averages of twice-daily outgoing longwave radiation (OLR) observed by satellite are used in this study to estimate the location and strength of tropical deep convection. This data set has been the basis for numerous studies of tropical convective activity, in which low values of OLR are indicate the presence of tall cumulus towers associated with intense convection. The data are obtained from NOAA’s polar-orbiting satellite as radiance measurements in an infrared window channel, which is then converted to a broad-band estimate of the total OLR (Gruber and Krueger 1984). The global observations are binned into a day and night observation on a 2.5° by 2.5° global grid. Here we use the unbroken 1979 through 1998 time series within the global tropical strip 15°S-15°N.

ECMWF operational twice-daily 10m zonal wind for the period 1985-99 (ECMWF 1993) was used as a check on the OLR results. All the analyses done with OLR were carried out identically with zonal wind, and some findings are cited below. But we chose to work principally with OLR since the results were very similar and the OLR time series is longer. Hendon et al (1999) also found parallel results analyzing MJO indices based on OLR and 850mb zonal wind.

The Southern Oscillation Index (SOI) is the monthly average sea level pressure difference between Tahiti and Darwin, Australia, demeaned and normalized by its standard deviation (Chelliah 1990). The time series used here were prepared by the National Centers for Environmental Prediction.

3. Analysis methods used to represent the MJO

A representation of the MJO, comparable to those used by other authors, was constructed from the OLR and zonal wind observations as follows. First the time series were bandpassed using complex demodulation (Bloomfield 1976), which is type of bandpass filter that gives the time variation of the amplitude and phase of a time series in a specified frequency band. Briefly, in complex demodulation, the time series is first frequency-shifted by multiplication with $e^{-i\omega t}$, where ω is the central frequency of interest. Then the shifted time series is lowpass filtered, which removes frequencies not near the central frequency. This acts as a bandpass filter when the time series is reconstructed. At each spatial location, the result can be expressed in the form $h(t) = A(t) \cos(\omega t - \phi(t))$, where $h(t)$ is the reconstructed time series, $A(t)$ is the amplitude and $\phi(t)$ the phase. The output of complex demodulation is equivalent to an ordinary bandpass, but has the advantage of explicitly expressing the result in terms of a time varying amplitude and phase that shows how the variance wanders within the frequency band. In the following, the central frequency ω was taken to be 2π/(40 days), with filtering that resulted in half-power limits between 27 and 72 days. Fig. 1a shows an example of the bandpassed OLR time series along the equator during 1991-93. All of the analyses were also carried out with a central frequency of 2π/(60 days), but little substantive difference was found in the results.

Second, the band-passed time series $h(x,y,t)$ were decomposed into orthogonal modes using singular value decomposition (SVD; Bretherton et al 1992) in the region 15°S-15°N, over the global tropical strip. Like the closely related EOF analyses (see Cherry 1997), SVD decomposes time-varying fields into products of orthogonal spatial patterns and temporal expansion coefficients. SVD is ordinarily used to find modes that maximize the covariance between two fields that are temporally synchronous but may span different regions. However, here we make use of a suggestion by Mike Wallace (personal communication, 1998) to analyze the propagating behavior of a single field by performing SVD on the field itself plus a second field constructed by time shifting the original field one-quarter period. (In doing this shifting, the explicit frequency given by complex demodulation is an advantage). SVD then gives eigenvector pairs that, combined, represent propagating variability. Fig. 2 shows the spatial patterns of the dominant quadrature mode pair for OLR, which together account for about 80% of the covariance (that is, the propagating variance of bandpassed OLR). One mode has oppositely-signed amplitude maxima in the Indian and Pacific Oceans, while the other is centered over the Indonesian Archipelago with smaller off-equatorial lobes to the east. The time coefficients (not shown) are highly lag-correlated one quarter period apart. These modes are quite similar to those produced by others, for example the mode pairs shown in Fig. 1 of Slingo et al (1999) or Fig. 4 of Shinoda et al (1998). Long experience with applying these techniques to the MJO suggests that any of several types of EOF-based modal decomposition generally produce similar results (H. Hendon, personal communication, 1999). As a check, an ordinary EOF decomposition of bandpassed OLR was performed; the spatial patterns and temporal coefficients of the EOF low mode pairs were essentially identical to those for SVD. We will refer to the fields reconstructed from the gravest quadrature pair SVD modes and their time coefficients as the “SVD reconstruction”. Fig. 1c shows an example of the field produced by this reconstruction. Two additional quadrature mode pairs were probably significant (North et al 1982), and the comparisons described below were checked by repeating them with these pairs included; where appropriate, these comparisons will be mentioned.

A novel type of MJO representation was constructed that will be seen to have an important property that the modal description lacks. The salient characteristics that an index of the MJO must have are: intraseasonal frequency, large zonal scale, and eastward propagation at a speed of a few $\mathrm{m\,s^{-1}}$. For example, such an index must exclude the spatially-incoherent signals that make up about half the intraseasonal variance over the west Pacific warm pool (Hendon et al. 1999). The EOF-based modal descriptions inherently have these properties because the the MJO is the dominant coherent intraseasonal signal in the tropics, and is always picked up by the lowest EOF modes. The new index was constructed without the use of EOF techniques as follows. First, the data were bandpassed by complex demodulation as was done for SVD. Inspection of the reconstructed fields $h(x,y,t)$ showed a predominance of eastward-propagating signals, but also some quasi-stationary, or westward-propagating, or small-spatial-scale signals (e.g. Fig. 1a). Then the bandpassed time series were filtered along trajectories ($x-ct$) to produce a field that conformed to the eastward-propagating, large-zonal-scale characteristics of the MJO. Filtering along trajectories was accomplished by time-shifting the fields, as a function of x, so that a signal propagating east at speed c became stationary in the shifted field. That is, the shifted field $g(x,t) = h(x,t+x/c)$. Then g was filtered in x using a strong zonal smoother with half-power at 87° longitude; this eliminated any variability that had small spatial scales or propagated at a speed not near c. Finally, the smoothed data were back-shifted to restore the correct time. This procedure is equivalent to smoothing h along a propagation path $(x-ct)$.

The speed c representative of the MJO was estimated empirically by carrying out the time-shifting and filtering described above for values of c between 1 $\mathrm{m\,s^{-1}}$ and 12 $\mathrm{m\,s^{-1}}$ in 0.5 $\mathrm{m\,s^{-1}}$ steps, which more than spans the range reported in the literature (Shinoda et al 1998; Rui and Wang 1990). The value $c = 5.5\ \mathrm{m\,s^{-1}}$ was found to retain the largest variance in the filtered field, although the peak was relatively broad and values of c between about 4 to 7 $\mathrm{m\,s^{-1}}$ carried similar variance (and subsequent analyses based on these fields also produced similar results).

The result of this smoothing along $(x-ct)$ is a field that contains only eastward propagation near the chosen speed, and has large zonal scale with no small-scale incoherent variability. In other words it retains the same salient MJO properties as the modal description, and therefore should be an equally valid representation of the MJO. Fields resulting from this time-shifting and filtering are referred to here as the "eastward-propagating part" (EPP), and an example is shown in Fig. 1b.

In this paper, all correlations cited are significant at the 95% level unless noted. Significance was estimated according to the procedure in Kessler et al (1996), based on estimating the degrees of freedom from the independence timescale of Davis (1976). Typically, the interannual correlations of the MJO representations with the SOI had 20-30 degrees of freedom in the 19-year time series, which resulted in correlations above about 0.4 - 0.45 being significant at the 95% level.

4. Comparison of the MJO representations

To show the patterns of interannual variability represented by SVD and EPP, in each case the reconstructed OLR fields were squared (both fields have zero mean), then filtered with a 1-year running mean, then Fig. 3 plots the square root of these running means along the equator. This will be considered as the interannual signal for each representation. The analogous patterns for 10m zonal wind were highly correlated with those for OLR and would be described similarly. The SVD pattern (Fig. 3, left) has two regions of large equatorial amplitude, near 80°E in the eastern Indian Ocean and near 140°E in the far western Pacific, with a local minimum over

Indonesia and almost no signal in the central equatorial Pacific (weak maxima occur poleward of 5° latitude in the central Pacific, as can be deduced from Fig. 2).

For present purposes, the most important feature is that the SVD interannual pattern in Fig. 3 is very nearly stationary in x, varying only in time. Its time history at a particular longitude differs from that at any other only in magnitude. This reconstruction from the first mode pair of course depicts eastward propagation at the intraseasonal timescale (not visible in the running average of Fig. 3, but seen in the example of Fig. 1c), but a quadrature pair of modes is not sufficient to represent both intraseasonal propagation and lower-frequency wandering of the envelope of variability. There aren't enough degrees of freedom to do both, so the MJO depicted by the SVD reconstruction is a standing envelope with intraseasonal oscillations propagating across it. Each individual MJO event occurs with very similar spatial structure and longitudinal position (Fig. 1c), and interannual variability consists of standing (in x) fluctuations that are time variations of intraseasonal amplitude only, not position, with little zonal phase difference. The second and third SVD quadrature pairs did not improve this situation very much, partly because their eigenvalues were at least three times smaller, and also because they represented primarily variability off the equator.

Interannual variability in the SVD representation can be compared with the analogous EPP fields in Fig. 3 (right). Many features are similar: the two bands of large amplitude over the eastern Indian and west Pacific Ocean, with a minimum over Indonesia, and the small signal in the central equatorial Pacific. But there is a crucial difference over the west-central Pacific, where the EPP representation shows enhanced MJO variance episodically extending eastward. Further, the EPP fields show significant differences between longitudes, differences that are excluded from the single-mode-pair SVD representation where the whole equator is in phase at interannual timescales. The 1991-93 example (Fig. 1) contrasts early 1991, when strong MJO variability occurred only over the Indian Ocean, with early 1992, when it extended well out over the Pacific. This longitudinal shift is well portrayed by the EPP representation (Fig. 1b) but the analogous SVD reconstruction (Fig. 1c) showed the same spatial patterns for both these cases. A misleading impression of vigorous MJO activity over the Pacific would be inferred from the SVD fields in this case. Sometimes the two EPP interannual maxima (Fig. 3, right) near 80°E and 140°E vary synchronously, but there are numerous occasions on which they do not. The reason the EPP fields allow interannual variability to vary with longitude is that this calculation is “local” (within the constraint of the 90° longitude smoothing), in contrast to the SVD mode fields which are represented by a single pair of modes that have maximized the overall variance represented. Finally, the two representations are significantly correlated with each over the Indian Ocean (note in Fig. 3 the relatively good correspondence between them at the 80°E maximum) but are much less so over the west Pacific.

The two representations of the MJO can now be compared with the SOI. An index of interannual variability of the MJO as portrayed by the SVD modes can be derived equivalently either as a time series from any longitude in Fig. 3 (left) (these will differ only in magnitude) or from the SVD temporal coefficients. This temporal index is uncorrelated with the SOI ($r = +0.09$) or other measures of the ENSO cycle, as has been pointed out by others based on similar indices (Hendon et al 1999; Slingo et al 1999), and including the second and third quadrature pairs did not improve the correlation much; it took at least 4 mode pairs before the correlation was significant. To demonstrate the difference between the SVD and EPP interannual MJO signals over the western Pacific, Fig. 4 (top) shows time series at 0°, 170°E (in the region where the interannual eastward expansion of MJO activity occurs) extracted from the two fields in Fig. 3, overlaid with the SOI (for simplicity, only OLR is shown, but the comparable time series based on the zonal wind data are very similar). Fig. 4 (bottom) shows that the east edge of strong MJO activity (defined as the 4 $\mathrm{W\,m^{-2}}$ contour of EPP in Fig. 3, right) moves east several thousand kilometers during El Niños. Interannual EPP at 0°, 170°E is significantly correlated with the SOI ($r = -0.50$) (a negative correlation indicates simultaneity of increased intraseasonal variance with El Niño). The correlation is visually obvious in the time series of Fig. 4, in which the EPP index shows increased MJO activity extending into the central Pacific during all the El Niños of this period (1982-83, 1986-87, 1991-92 (continuing through the weak warm event of early 1993), 1994-95 and 1997-98. There are two other peaks of MJO activity indicated by the EPP index in Fig. 4 that do not correspond to El Niño events: in 1979-80 and 1989-90 (note that both these periods have maxima in the SVD index as well, and are also weak negative peaks of the SOI). It is also worth noting that at the time there was much discussion of the “aborted El Niño of 1989-90" (B.Kessler, personal communication, 2000), as conditions during 1989 appeared to be setting up a warm event. SST in the equatorial Pacific west of 150°W was 0.5°-1°C anomalously warm during 1989-90, so this may have been comparable to a “pre-Niño” period.

5. Discussion

Two interannual indices of MJO activity have been developed and compared: one (SVD) based on an EOF decomposition that is similar to indices that have been used by many other authors, and another (EPP) that is an essentially local calculation that identifies large-scale, eastward-propagating intraseasonal variability directly.

In evaluating the possible connection between the MJO and the ENSO cycle, the important difference between the two indices is that the SVD index is uncorrelated with the SOI or other measures of the ENSO cycle, while the EPP index over the Pacific shows a clear connection between MJO activity and El Niño events. The difference occurs because the SVD index (in common with previously-developed EOF-based MJO indices) is made up of a single quadrature pair of modes. Such a quadrature pair reproduces very nicely the eastward propagation of the MJO *at the intraseasonal timescale*, but cannot, with only two spatial patterns, also represent the east-west wandering of the envelope of intraseasonal variability. Nor did including the second and third SVD mode pairs produce significant changes in the interannual envelope. Therefore the SVD fields appear as a standing (in x) envelope extending from the Indian Ocean to the western Pacific, with nearly identical intraseasonal oscillations propagating across it. The interannual variability represented thus consists only of x-independent temporal amplitude fluctuations, and this signal does not appear to have much connection to the ENSO cycle. This has led some to conclude that the MJO cannot have a connection to ENSO.

However, the EPP index demonstrates that the zonal envelope within which intraseasonal propagation takes place meanders east and west (Fig. 3, right panel, and Fig. 4, bottom), and that this aspect of MJO interannual variability is well-correlated with the ENSO cycle, such that each of the El Niño events of the past 20 years occurred in conjunction with an eastward extension of the region of MJO activity to the central equatorial Pacific. This meandering is excluded from indices based on EOF mode pairs.

There is no doubt that composite MJO events represented by EOF modes have shown great utility in gaining understanding of the evolution of the MJO phenomenon itself. To cite two examples, Shinoda et al (1998) used an EOF-based composite MJO event to evaluate the lag relation between MJO ocean-atmosphere heat fluxes and SST. Maloney and Hartmann (1998) examined the moisture convergence in a composite event and also showed the relation between the phase of an MJO and active periods of the Indian monsoon. EOF-based composites are entirely appropriate for such purposes. But in assessing the possible MJO-ENSO connection, a depiction of the MJO that systematically excludes east-west meandering of the zonal envelope is fundamentally flawed and predetermines a negative conclusion. Similarly, evaluating ocean-atmosphere interaction based on a composite MJO may not be germane to ENSO because it doesn't take into account variations in the zonal position of the intraseasonal oscillation relative to interannual changes in SST.

It is worth thinking about the requirements for indices of the MJO needed to evaluate the MJO-ENSO connection, since these appear to be distinct from indices used to study the MJO itself. First, since the development of an El Niño event is an ocean-atmosphere interaction in the Pacific, it is the Pacific winds that are significant. EOF mode representations of global intraseasonal variability are necessarily going to focus substantial weight on the Indian Ocean region that may be less relevant to ENSO. Second, the average eastern edge of the MJO envelope occurs over the west Pacific warm pool, a few thousand km from the western boundary (along the equator). Relatively small shifts in the position of the MJO region can therefore produce relatively large proportional changes in the fetch of the MJO winds over the Pacific. Third, the evolution of an El Niño event involves nonlinear ocean-atmosphere feedbacks. Air-sea exchanges evaluated from a fixed-position MJO composite cannot adequately address these feedbacks.

There are at least two facets of MJO interannual variability: the amplitude of zonal-average intraseasonal variations, and the zonal position of the MJO envelope. Indices based on EOF modes of global fields tend to represent only the first of these, which may not be the most important aspect of the interaction between the MJO and El Niño. The relatively crude EPP index studied here may not be the best solution, but it does point to the need to develop indices that capture both aspects in understanding the possible connection between the MJO and the ENSO cycle.

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