Loss of Significance and Multidecadal Variability of the Madden–Julian Oscillation

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ABSTRACT

Change in significance and multidecadal variability of the Northern Hemispheric winter MJO during 1948–2006 is examined using NCEP–NCAR reanalysis data. Variation of the MJO power relative to a red background is estimated by isolating the MJO signal through frequency–wavenumber spectral analysis using a 10-yr sliding window. It is shown that during the period of study, the rate of increase of background power has been larger than the rate of increase of the MJO power, leading to a decreasing trend of significant MJO power. It is also found that a multidecadal variation rides on the decreasing trend of significant power of the MJO. Another finding is that the zonal mean component of the zonal wind at 200 hPa on a MJO time scale has a significant increasing trend. Both of the above trends are statistically significant at the 95% confidence level.

Energetics calculations in the wavenumber domain were carried out to understand why the significant MJO power is not increasing as fast as the red background. It is shown that long waves (wavenumbers 1–3, i.e., the MJO scale) lose energy to the zonal mean flow and the rate of kinetic energy gain by the zonal mean flow from the long waves has a linear increasing trend. Thus, while the MJO is also being energized by a warming ocean, it is losing increasingly more energy to the zonal mean flow, making the zonal mean more energetic while losing its own significance at the same time. It is found that the observed multidecadal variability of the significant MJO power has no relationship with other well-known multidecadal variability. However, the authors find that the multidecadal variability of the MJO and the rate of kinetic energy exchange between the zonal mean flow and long waves are closely linked, indicating that the observed multidecadal variability of the MJO is internally driven.

1. Introduction

A convectively coupled eastward propagating oscillation with periods between 20 and 70 days and wavenumber between 1 and 3 (Lau and Waliser 2005), the Madden–Julian oscillation (MJO) is an ubiquitous mode of variability in the tropical atmosphere and is most active during boreal winter (Madden and Julian 1994). The oscillation is invigorated over the warm waters of the tropical Indian Ocean (IO) and western Pacific (WP) with strong convective coupling leading to slow eastward propagation while it propagates faster in the Eastern Hemisphere like a free mode. While on one hand the MJO influences seasonal to interannual predictability (Kessler and Kleeman 2000; Zhang et al. 2001), on the other it influences weather predictability by modulating the frequency of occurrence of synoptic events such as lows, depressions, and tropical cyclones (Maloney and Hartmann 2000; Jones et al. 2004; Bessafi and Wheeler 2006). The amplitude of the MJO is much larger than that of the interannual variability (IAV) of the seasonal mean and is comparable to that of the seasonal cycle (Waliser 2006a). The large amplitude, coupled with the fact that the MJO is associated with coherent oscillatory evolution (Wheeler and Hendon 2004), provides optimism for extended-range prediction of the oscillation. Quantitative estimates of potential predictability of the MJO (Waliser et al. 2003; Waliser 2006b) indicate that the limit of useful skill in predicting the active-break spells may be extended to 25–30 days.

As the genesis and growth of the MJO depends on the warm waters of the tropical IO and WP, any significant change of sea surface temperature (SST) would influence the convective coupling and affect the space–time characteristics of the MJO (Wang and Xie 1998; Waliser et al. 1999). Over the past 50 years there has been a clear increase in SST in the tropical IO as well as the tropical WP (Fig. 1c). The warming increases the moisture-holding capacity of the tropical atmosphere (Trenberth et al.
making it more convectively unstable (Riemann-Campe et al. 2009) and increasing the frequency of occurrence and intensity of high frequency events (Goswami et al. 2006). It is possible that the energy accumulated at smaller scales due to higher intensity of the high frequency events may cascade energy to larger scales and eventually make the MJO more energetic. Is it also possible that the atmosphere may preferably pump energy into MJO space and time scale: If not, where does the extra energy go? If the system preferably excites the MJO scale and makes it more energetic, the variance explained by the MJO should be higher than the background red spectrum. The objective of this study is to address these questions. Earlier discussion on MJO indices that measure MJO activity clearly point out the need for separation of the signal from the background. How do we isolate and quantify the signal from the background? The normalized wavenumber–frequency spectra introduced by Wheeler and Kiladis (1999) is a method that enables us to estimate the background and isolate the true MJO and other convectively coupled oscillations of the tropical atmosphere.

Most earlier works on interannual variability (IAV) of the MJO tried to establish the physical link between the MJO and the El Niño–Southern Oscillation (ENSO) (Slingo et al. 1999; Hendon et al. 1999; Teng and Wang 2003). An intraseasonal index was constructed by Slingo et al. (1999) over the equatorial region using bandpass-filtered upper-air zonal mean wind. They found a significant shift in activity around the mid-1970s that also shows a linear increasing trend. Another set of interannual MJO indices was developed by Hendon et al. (1999) using outgoing longwave radiation (OLR) and the zonal wind at 850 hPa. Their first measure of the MJO is the variance of the wavenumber–frequency-filtered OLR and zonal wind while the second one is based on empirical orthogonal function (EOF) analysis of OLR and zonal wind, which is widely used to identify the dominant eastward propagating signal. Although these two studies could not present clear quantitative evidence for the association between the MJO and ENSO, they showed the linear increase in MJO activity. In a recent study, Jones and Carvalho (2006) investigated the changes in activity and statistical significance of the linear trend in the MJO since the mid-1970s using the zonal wind at 850 and 200 hPa. They captured MJO events based on combined EOF (CEOF) analyses of the zonal wind at 850 and 200 hPa and constructed an MJO index that also showed a linear increasing trend.

Is this linear trend in IAV of tropical ISV really attributable to the MJO, which is a symmetric, eastward propagating equatorially trapped, wavenumber 1–3, and 20 to 70-day periodic convectively coupled oscillation?
Do these MJO indices, which were intended for measuring IAV of the MJO, really take into account the salient features of the MJO? Though the zonal mean and bandpass-filtered indices capture MJO variability indirectly, they also include the variability caused by all resolvable spatial scales that propagate both eastward and westward. The zonal wind at 200 hPa has a significant westward propagating component at the MJO time scale. Hence, a significant fraction of the variability explained by the zonal mean and frequency-filtered MJO indices may be unrelated to MJO activity. EOF analysis may be a better method of capturing the MJO activity since it objectively selects dominant modes of variability. However, as only the first two EOFs can be used for depicting global-scale MJO activity (Kessler 2001), the spatial structure is essentially prescribed. Hence, EOF-based indices are not suitable for the study of IAV of the MJO. Above all, the tropical atmosphere is basically red in nature (Salby and Hendon 1994; Wheeler and Kiladis 1999). None of the past MJO indices separated the background from the raw signal, so the IAV of the MJO shown in earlier studies might not come from a pronounced spectral peak but from part of a red background.

Our study specifically addresses the following important issues. 1) What is the nature of Northern Hemisphere (NH) winter MJO variability at the multidecadal time scale, and how do we quantify it? 2) Does the multidecadal NH winter MJO variability show a linear increasing trend: if not, why? 3) What role does the exchange of energy between the zonal mean flow and waves play in the significant multidecadal NH winter MJO variability? In section 2, we discuss the datasets used in this study. In section 3, we discuss at length the issue of isolation of the red background from the signal. In section 4, we present the observational evidence for changes in significance of the MJO activity and its multidecadal variability. In section 5, we examine the role of the multidecadal energy exchange between the zonal mean flow and waves on the multidecadal MJO activity. In section 6, we present a discussion on the sensitivity of the trend and multidecadal variability of the MJO on the method of estimation of red background, on ENSO and Indian Ocean variability and on the quality of the reanalysis. Finally, our findings are summarized in section 7.

2. Data and methodology

The study of multidecadal variability of the MJO demands a long, coherent, dynamically consistent comprehensive dataset that resolves low-frequency intraseasonal variability and its associated trend. Reanalysis projects aim to produce such a long, accurate, comprehensive, and dynamically consistent record of the atmospheric evolution using a fixed, state-of-the art assimilation system and the best available observations including all ground- and ship-based observations, radiosondes, satellite observations, and different model outputs. Hence, the core analysis presented in this paper is made using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) daily zonal wind at 200 hPa ($U_{200}$) for the 1948–2006 NH winter seasons, which include November–February (NDJF). The NCEP–NCAR reanalysis products of the daily zonal wind at 850 hPa ($U_{850}$) and OLR were used for validating the results, and the meridional winds at 200 and 150 hPa, the zonal wind at 150 hPa, and omega at 150 and 250 hPa were also used for the computation of the kinetic energy exchange between the zonal mean flow and waves at 200 hPa. To filter out the 20–70-day frequency band, we applied a Lanczos filter (Duchon 1979). To examine the changes in tropical sea surface temperature (SST), we used the National Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST_V3 data provided by the NOAA/Office of Atmospheric Research/Earth System Research Laboratories/Physical Sciences Division (OAR/ESRL PSD), from their Web site [http://www.cdc.noaa.gov/; see also Smith et al. (2008)].

To augment our confidence in the multidecadal variability of the MJO derived from the NCEP–NCAR reanalysis, we repeated the analysis using the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) (Uppala et al. 2005) data. Since the length of ERA40 is limited to 1958–2001, the data length is extended to 2006 using the ERA Interim daily dataset.

We use space–time spectral analysis to identify and isolate the MJO. For this purpose, daily anomalies of $U_{200}$ are constructed by removing the seasonal cycle. Anomalies for the 59 NH winter seasons (NDJF) (120 days, 1948–2006) are combined and used for estimating the space–time spectra. Since the MJO represents the equatorially trapped symmetric mode, we limit our domain of interest to the region between 15°N and 15°S. Different 120-day segments are selected using a 60-day overlap. After removing the trend from each segment, a complex fast Fourier transform (FFT) is performed in longitude, for each latitude and time, and complex FFT is again applied in time for each latitude on the resultant Fourier coefficients. The wavenumber–frequency power spectrum is derived by multiplying the result with its complex conjugate. The power spectrum is computed for each of the available segments and averaged. The average power is summed over the latitudes of interest to obtain the space–time power spectra.

The distribution of space–time power of the symmetric wavenumber–frequency spectra indicates the red nature
of the tropical atmosphere. To test the statistical significance of spectral peaks, an estimate of the red background is required. We estimate the red background following an empirical method used by Wheeler and Kiladis (1999). This is done by passing a 1–2–1 filter through the power repeatedly in both wavenumber and frequency. The statistical significance of the spectral peak is then estimated by computing the ratio of raw spectra to the red background and comparing this value with a chi-squared test with the corresponding number of degrees of freedom (dof). The dof of the wavenumber–frequency power spectrum can be calculated as 2 (amplitude and phase) × 6 (number of independent latitudes) × 59 (number of seasons). See Wheeler and Kiladis (1999) for more details.

3. Isolation of the MJO signal

A transient of the tropical atmosphere, the MJO is affected by the underlying ocean through the exchanges of heat and moisture fluxes (Sobel et al. 2008). With the tropical SST having a linear trend (see Fig. 1c), we may expect a similar trend in the MJO as well. However, in order to bring this out, it is imperative that we isolate the MJO signal from other similar intraseasonal variability (ISV).

First, we examine the simplest metric of the tropical ISV, namely the variance of the 20–70-day bandpass-filtered $U_{200}$ and $U_{850}$ fields. Figure 1 shows the zonally averaged variance of the 20–70-day-filtered mean zonal wind ($U_{200}$ and $U_{850}$) in the latitudinal belt between 15$^\circ$S and 15$^\circ$N, calculated using a 10-yr (NDJF) sliding window. The analysis is repeated separately for the Eastern and Western Hemispheres. It may be noted that variance of the ISV in the Eastern Hemisphere is about one-half of that in the Western Hemisphere. From Fig. 1a, a linear increasing trend is noted in the zonally averaged ISV variance of $U_{200}$ over the Eastern Hemisphere, with $\sim$60% increase in variance since the 1950s. On the other hand, the variance of $U_{200}$ in the active Western Hemisphere increases linearly up to 1970 but remains steady afterward. The variance of $U_{850}$, (Fig. 1b) shows no significant trend in the Western Hemisphere. However, it does show a multidecadal variability in ISV activity.

The linear increasing trend of tropical ISV may be understandable in the context of a recent warming environment, as seen from the increasing trend in tropical SST over the IO and WP (Fig. 1c). It appears that the energetic tropical atmosphere is pumping more energy at the intraseasonal time scale, as evident from the increase in variance at the 200-hPa level, where dissipation is weak (Fig. 1a). That the variance at 850 hPa does not show an increasing trend may be due to the fact that there is far more dissipation at the 850-hPa level.

the warm ocean may pump more energy for the ISV at 850 hPa, it also makes the dissipation more vigorous and takes more energy out of the ISV, thereby keeping the power more or less at the same level.

However, the variance of tropical ISV at the 20–70-day time scale, as shown in Figs. 1a,b, may not come entirely from the MJO. Figure 2 shows the symmetric wavenumber–frequency power spectra for the winter seasons (NDJF) of 1948–2006 from the NCEP–NCAR reanalysis: the zonal winds at (a) 850 mb and (b) 200 mb. Contour interval is 0.3 from the outermost contour with 1.1 (thick line). The magnitude of the ratio above 1.09 is statistically significant at the 95% confidence level (based on 700 dof).
westward propagating mode. Therefore, so as to interpret the cause of the increasing trend in variance in Fig. 1a, in addition to the red background, we have to separate the contribution of the westward propagating component to the trend.

Therefore, instead of using a simple temporal filter, MJO is isolated by using space–time spectral analysis (Wheeler and Kiladis 1999) and focusing on the mode between eastward wavenumbers 1–3 within periods 20 and 70 days. We shall now examine the trend of the MJO power isolated in this manner.

4. Trend and multidecadal variability of significant MJO activity

The normalized wavenumber–frequency power spectrum introduced by Wheeler and Kiladis (1999) is adopted for extracting the significant MJO variance by comparison with the background red spectrum. From the recent warming of the tropical ocean, we can assume that the nature of the variability imprint on the MJO would be different before and after the warming. Figure 3 shows the ratios between raw and background wavenumber–frequency power spectra of $U_{200}$ for two regimes, namely the 1948–76 (Fig. 3a) and 1977–2006 winter seasons (Fig. 3b). In these figures, only those ratios significant at the 95% confidence level are shown. There are significant changes in the space and time distribution of the variance of convectively coupled waves including the MJO. During the earlier period, the peak power occurred for wavenumber 1 at period $\sim 40$ days while during the later period the peak power shifted to wavenumber 0 at period $\sim 60$ days. The most striking feature is that in recent years there is a significant increase in power at wavenumber 0, that is, zonal mean flow in the 20–70-day frequency band. Also, the significant power of the westward mode has been shifted to higher wavenumbers.

To test whether the changes in the space–time spectra derived from the NCEP–NCAR reanalysis are robust, we calculated space–time spectra of $U_{200}$ from ERA-40. As the data length is limited for ERA-40, the first period is considered between 1958 and 1977. The space–time spectra derived for ERA-40 are shown in Fig. 4. It is clear that they are almost identical to those obtained.
from the NCEP–NCAR reanalysis. Thus, the loss of significance of the MJO and the increase in power of the zonal component appear to be robust conclusions.

To illustrate any long-term trend and multidecadal variation of the MJO, the wavenumber–frequency power spectral analysis is carried out for $U_{200}$ from the NCEP–NCAR reanalysis for all 1948–2006 winter seasons using a 10-yr sliding window, advanced 1 yr at a time. The power averaged over wavenumbers 1–3 and the 20–70-day period for the first 10-yr (i.e., 1948–57) interval is taken as the metric of multidecadal variability of the MJO for the year 1952. The repetition of the same analysis with a 10-yr sliding window will show how the significance in MJO activity has been affected. The significant westward mode is also quantified by taking the averaged power over the wavenumbers $-4$ to $-2$ and 20–70-day period. Figure 5 presents the multidecadal variability of raw and background MJO power, raw and background power of the westward mode, and raw and background power of the zonal mean (wavenumber 0) in the 20–70-day period. Figure 6 displays the significant power above the red background as shown by the raw/background MJO power, raw/background power of the westward mode, and raw/background power of wavenumber 0 in the 20–70-day period.

After an initial rapid increase during the 1950s, the MJO power remains more or less steady during the rest of the period (Fig. 5a). While the power of the westward propagating component at the 20–70-day time scale shows some indication of a multidecadal oscillation (Fig. 5b), the power in the zonal mean component has increased steadily (Fig. 5c). It is interesting to note that the power of the red background has increased almost linearly in all three cases. When we examine the significant MJO power, that is, the raw MJO power–background, while there is a multidecadal variability of $\sim 30$ yr, the ratio of MJO power with respect to the red background is steadily decreasing (Fig. 6a). As the significance of the MJO signal depends on how large the MJO power is with respect to the red background, this ratio essentially represents “significant power” of the MJO. Hence, we interpret this as the MJO losing “significance.” The conclusion is the same for the westward propagating mode as well (Fig. 6b). Another remarkable characteristic is the creation of power in the zonal mean flow at the 20–70-day frequency band over recent years. The significance of the zonal mean mode increased steadily and doubled over the 50-yr period (Fig. 6c). To support our view that the significant multidecadal MJO power is decreasing, the same analysis was repeated with the $U_{850}$ and OLR fields for the 1979–2006 winter seasons and is presented in Fig. 7. Both OLR and $U_{850}$ similarly show a decreasing trend in the significant MJO power although not as strong as for $U_{200}$.

To test whether the loss of significance and the interdecadal variability of the MJO and increasing trend of the zonal mean component at the 20–70-day time scale obtained from the NCEP–NCAR reanalysis (Fig. 6) are robust signals, space–time spectra of $U_{200}$ from ERA-40 using a similar sliding window were analyzed. Results from this analysis for significant power for the MJO, the westward propagating mode, and the zonal mean component are shown in Fig. 6 by dashed curves. It is clear that, although there are some minor differences in the magnitude of significant power, the multidecadal variability and trend seen from the ERA-40 data are almost identical to that obtained from the NCEP–NCAR reanalysis. Thus, we believe that the observed multidecadal variability and trend are physical.
Why is MJO losing its significance even though the atmosphere and ocean are warming? Also, what is responsible for the multidecadal variability of the significant MJO power? The reason behind the decreasing trend of significance of the MJO variance is that the rate at which the increase in convective coupling is adding energy to the MJO is slower than the rate at which the same process is increasing the red background power, clearly seen from Fig. 5. It may be easier to understand why the red background is increasing. We hypothesize that the conditionally unstable tropical atmosphere becomes more unstable due to prolonged warming of the tropical ocean, which leads to an increase in number and intensity of high-frequency extreme events. The accumulation of energy at smaller scales eventually cascades energy to larger scales and makes the tropical atmosphere more red. Why then is the power of the MJO not increasing at the same rate as the red background? One possible scenario is that, while the MJO may be energized by the convective coupling at the same rate, it may also be losing energy to other space and time scales at a faster rate. It is well known that wavenumber 1 loses energy to other scales through nonlinear interactions (Kanamitsu et al. 1972). There may be a connection between this problem and that the energy in the zonal mean at the same time scale is increasing steadily (Fig. 5). There is no known external forcing for the zonal mean at the 20–70-day time scale. Therefore, it is most likely that the zonal mean is gaining more and more energy due to more efficient cascading of energy from other scales of motion. We hypothesize that increased upscale cascading of energy from wavenumber 1 (MJO) is the primary reason for the recent amplification of the zonal mean flow variance and the cause for decreasing significance of the MJO. To test our hypothesis, the kinetic energy exchange between the zonal mean flow and waves is employed and the results obtained from it are presented in section 5.

5. Kinetic energy exchange between zonal mean flow and waves

By decomposing the equations of motion of the atmosphere, expressed in spherical coordinates, into wavenumber domain Saltzman (1957) formulated a method with which the rate of change of kinetic energy and available potential energy of a disturbance at a given
wavenumber can be estimated using a daily dataset. Different studies using both observations and numerical model output have shown that this method can be adopted for calculating the rate of change of kinetic energy for a given scale as a result of its interactions with other scales (Murakami and Tomatsu 1964; Saltzman 1970; Kanamitsu et al. 1972; Hayashi 1980). Calculation of the rate of kinetic energy involves three important processes. First, we consider the transfer of kinetic energy to the scale of wavenumber \( n \) from pairs of other wavenumbers \( m \) and \( p \). This is restricted by a trigonometric selection rule; that is, \( n = m + p \) or \( n = |m - p| \) for an exchange. Hence, it is also known as a triad interaction. Second is the gain of kinetic energy of a given "wavenumber \( n \) when it interacts with the zonal mean flow. Finally, the growth of kinetic energy for a given wavenumber is from the eddy available potential energy at the same scale.

The energy exchange between waves and waves and between waves and the zonal mean for the tropics using \( U_{200} \) for the NH summer season was calculated by Kanamitsu et al. (1972). They found that wavenumber 1 acts as the primary source for the tropics by supplying a significant amount of energy to the zonal mean. A simpler method of estimation of the nonlinear energy transfer by the cross-spectral method was proposed by Hayashi (1980), which is applicable in both wavenumber and frequency domains. To test our hypothesis, we employed the Hayashi method for calculating the kinetic energy exchange between the zonal mean flow and individual waves \((K_0, K_n)\). A positive (negative) sign for \((K_0, K_n)\) indicates that the zonal mean is losing (gaining) energy to (from) wavenumber \( n \). The kinetic energy exchange between the zonal mean flow and each wave for each of the 1948–2006 winter seasons is calculated. The sum of the kinetic energy between the zonal mean flow and individual waves gives the net kinetic energy exchange between them. This is calculated using all resolvable waves, and a 10-yr running mean of the net exchange is presented in Fig. 8a. The net kinetic energy exchange between the zonal mean flow and waves exhibits a multidecadal oscillation. During the first 10-yr period, the kinetic energy transfer was from the zonal mean flow to the waves. After that it changes sign and transfers kinetic energy from the waves to the zonal mean flow until 1979. During the 1980s, again it changes sign and the zonal mean flow loses energy to the waves. Since the early 1990s, the zonal mean flow becomes energetic by drawing kinetic energy from the waves. The net kinetic energy exchange between the zonal mean flow and waves shows a negative trend, indicating that the zonal mean is steadily gaining energy from the waves.

There are some indications in the multidecadal variability of a significant MJO (Fig. 6a) that is linked to the net exchange of kinetic energy between the zonal mean flow and waves. During the late 1950s and the 1980s, MJO activity was high (Fig. 6a) and at the same time the supply of kinetic energy was from the zonal mean flow to waves (Fig. 8a), making the waves more energetic. This contribution of kinetic energy might have gone to the MJO scale, which is reflected in the high MJO activity at that time. On the other hand, the loss of energy from waves to the zonal mean flow displays a close correspondence with the decline in MJO activity. To make things clearer, the kinetic energy exchange between the zonal mean flow and waves is separated into the exchange of the net kinetic energy between the zonal mean flow and planetary-scale long waves, that is, wavenumbers 1–3, and similarly between the zonal flow and the
remaining waves. The analysis results are presented in Figs. 8b,c.

It is apparent from Fig. 8b that the kinetic energy always flows from the planetary-scale waves (MJO) to the zonal mean flow, and it also shows a linear increasing trend. However, the transfer of kinetic energy from the planetary-scale waves to the zonal flow diminishes during high MJO activity and the transfer becomes substantial when the MJO power decreases. The multidecadal variability of energy transfer from the MJO scale to the zonal scale (Fig. 8b) is closely linked with the multidecadal oscillation of significant MJO power, seen in Fig. 5a. Thus, even the multidecadal variability of the MJO seems to be related to the exchange of energy between the MJO scale and the zonal scale. On the other hand, from Fig. 8c it can be seen that the other waves always draw energy from the zonal mean flow. Even though it also shows multidecadal variability, but there is no trend. A close examination of all the results of the kinetic energy exchange between the zonal mean flow and waves underscores our hypothesis that the extra energy due to continuous warming collected at smaller scales cascades upscale and eventually makes the zonal mean flow more energetic.

6. Discussion

a. Sensitivity to calculation of the red background

We describe the decreasing significance of the MJO by comparing the MJO power with the red background in Fig. 6a. Therefore, the trend and multidecadal variability of the MJO, in this study, may be affected by the way one estimates the red background. As mentioned in section 2, we followed the empirical method used by Wheeler and Kiladis (1999) in which we passed a 1–2–1 filter through the power repeatedly in both wavenumber and frequency. This process essentially smoothes out all of the peaks and enhances the background. While we believe that this is a reasonable way of estimating the red background, it is not objective. Here, we examine whether the trend and multidecadal variability of the MJO as found would be affected if we use a theoretically estimated red background spectrum. To do this, we follow Hendon and Wheeler (2008). Following Gilman et al. (1963), the red frequency spectrum is estimated as a lag \(-1\) autoregressive process by using the lag \(-1\) autocorrelation at each eastward and westward zonal wavenumber, obtained by inverse Fourier transform of the averaged symmetric-antisymmetric power spectrum. The red background power estimated this way and averaged for the MJO wavenumbers and frequencies is shown in Fig. 9a, and the ratio between MJO power and this background is shown in Fig. 9b. Comparison with the background power estimated by the empirical method (Fig. 5a) shows that the theoretical red background power is systematically slightly higher than that estimated empirically. As a result, the significant MJO power (raw/background) in Fig. 9b is about 20% smaller than that estimated in Fig. 6a. However, the trend and multidecadal variability estimated by us (Fig. 6a) is robust and remains completely unchanged by the change in estimation of the background red power. As the ratio required to be significant at the 95% confidence level is 1.38, another point to note is that the MJO power has decreased below the level required to be significant in recent years (post-1990s).

b. Role of ENSO and Indian Ocean variability on the trend of the MJO

ENSO, being the dominant mode of interannual variability in the tropical ocean–atmospheric system, leads to significant modulation of the large-scale dynamic and thermodynamic conditions of the tropical atmosphere–ocean system at this time scale (Wallace et al. 1998;
As the MJO is an instability depending crucially on slowly varying background mean conditions, it is reasonable to ask if the trend and multidecadal variability of the MJO, as shown here (Fig. 6a), could be contributed by any trend and multidecadal variability that ENSO may have. To test this possibility, we recalculate the MJO variance after removing the ENSO-related variability from the data. Representing ENSO with the Niño-3 index (area-averaged SST over $5^\circ S$–$5^\circ N$, $150^\circ W$–$90^\circ W$), daily NH winter (NDJF) $U_200$ data at all grid points are regressed with the Niño-3 index. The variance of the 20–70-day bandpass-filtered zonal winds for the 1948–2006 winter seasons using a 10-yr sliding window averaged over the tropical belt ($15^\circ S$–$15^\circ N$, $0^\circ$–$360^\circ$). Dotted line represents the variance calculated using the filtered data from which the ENSO effect has been removed. Dashed–dotted line represents the variance calculated using unaltered data.

Their concern is based on the premise that the regime shift observed in reanalysis data is entirely due to a change in the observing system in the form of the infusion of large volumes of satellite data. However, we believe that the trends obtained from reanalysis, such as the NCEP–NCAR reanalysis, are not entirely an artifact of changing observing systems in the mid-1970s. We have reason to believe that the mid-1970s regime shift is physical and part of a large-scale multidecadal variability of the tropical coupled ocean–atmosphere system. Zhang et al. (1997) using Comprehensive Ocean–Atmosphere Data Set (COADS) SST data showed that there is an ENSO-like multidecadal variability with a regime shift in the mid-1970s. As this SST data did not have much satellite input, we believe that the regime shift in SST in the mid-1970s is real. The large-scale SST trend, such as that shown in Fig. 1c, is unlikely to be affected by an increase in data during the satellite era. We believe that the trend in circulation from reanalysis products is not completely spurious since it has a large spatial scale and is strongly coupled to the trend of the large-scale SST (Garreaud and Battisti 1999; Goswami 2005). Another reason we believe that the regime shift in the mid-1970s is real is based on the fact that a completely independent 54-yr rainfall dataset from rain gauge observations over the Indian monsoon domain shows a mid-1970s regime shift in monsoon intraseasonal oscillations, consistent with large-scale circulation changes seen in reanalysis products (Suhas and Goswami 2008). The presence of a signature of the regime shift in this independent dataset affirms that some of the variability obtained from reanalysis datasets is physical. While the presence of some spurious variability cannot be ruled out completely, the use of two independent reanalysis datasets as well as indirect support from independent datasets give us some confidence that the trend and multidecadal variability of the MJO brought out in this study are real.

c. Reanalysis data and long-term trend

The mid-1970s regime shift and associated increase in SST and convection over the central Pacific and its connection over different parts of the globe have been reported mainly using NCEP–NCAR reanalysis datasets (Goswami 2005). Whenever reanalysis data is used to study trends or multidecadal variability, there are some concerns about the effects of changes in the observing system after the satellite era leading to a spurious climate shift (Wu and Xie 2003). Reliability of reanalysis products on climate variability and trends was examined by Bengtsson et al. (2004) within the context of changes to the global observing systems and they cautioned against interpreting any climate trends obtained with reanalysis products.

7. Summary and conclusions

In this study, we mainly focused on the changes in significant NH winter MJO activity on longer time scales...
and the importance of isolation of the MJO variance from the red background. We have discussed various MJO indices introduced by past studies and brought to light the fact that some of the variance explained by those indices came from the red background nature of the tropical atmosphere. We have also demonstrated that a fraction of the ISV in the period range between 20 and 70 days can come from significant westward-propagating low frequency disturbances. Since the zonal mean index constructed by Slingo et al. (1999) and other variance-based MJO indices applied bandpass filtering only in the frequency domain, it implicitly includes all resolvable spatial scales that propagate both eastward and westward. To focus on the true MJO variance, we employed a normalized wavenumber–frequency power spectra, which is a method that separates the red background from the MJO power. To highlight the longer time-scale variability, the averaged space–time power over wavenumbers 1–3 in a 20–70-day period band is calculated using zonal wind data at 200 hPa taken from the NCEP–NCAR reanalysis for the 1948–2006 winter seasons with a 10-yr sliding window and it is taken as our MJO metric. Even though the raw MJO power shows a linear increasing trend in the 1950s, it remained almost steady for the rest of the period. However, the background power has steadily increased, making the MJO power less distinct from the red background. We examined the validity of this result with other variables such as $U_{850}$ and OLR and found a consistent outcome. However, when we examine the significant MJO power (raw/red background power), it is seen to have a decreasing trend with multidecadal variability at roughly 30-yr periodicity riding on it. There are also significant changes in the westward-propagating low frequency variability. The significant power of the westward mode shifted from wavenumber $-2$ to $-4$. Another interesting fact noted in the space–time power spectral analysis is the steady and significant amplification of the zonal mean flow in the 20–70-day band.

Three questions need to be answered. 1) Why is the atmosphere becoming more red? 2) Why is the significance of the MJO declining? 3) What is responsible for the increasing power in the zonal mean component on the MJO time scale? To seek answers to these questions, we note that the warming of the tropical ocean is increasing the moisture-holding capacity of the tropical atmosphere, making it more conditionally unstable. This may lead to more high frequency events accumulating energy at smaller scales, which may eventually cascade energy to the planetary scale and zonal mean flow, making them more energetic. An observed increase in the frequency of occurrence and intensity of extreme events (Goswami et al. 2006) supports the conjecture that the tropical atmosphere is becoming more unstable (Mani et al. 2009). The cascading of energy may not be restricted only to the MJO scale but may also be distributed among other space and time scales. This explains why the atmosphere is becoming more red. Increases in the efficiency of convective coupling could also selectively add more energy to the MJO scale. Why then the significance of the MJO declining? We propose that this is because the MJO is losing more energy to other scales of motion than gaining from convective feedback in a warming environment. In particular, we propose that the MJO is losing more energy to the zonal mean component at the MJO time scale in recent years, which explains why the zonal mean component is increasing in strength.

To prove our hypothesis, we computed the exchange of kinetic energy between the zonal mean flow and waves. We found that the supply of kinetic energy from the planetary scale to the zonal mean flow has increased, making the zonal mean flow more energetic in recent years. Also, there is a multidecadal variability in the net exchange between the zonal mean flow and waves that appears to be directly linked to the multidecadal variability of MJO activity. The net exchange of kinetic energy between the zonal mean flow and waves becomes positive when the MJO exhibits high activity and negative when MJO power is diminished. Even though MJO power has also increased in recent years, the rate of its increase has been slower than that of the red background, making it less significant in recent years. This is in contrast to earlier results, which showed an increasing trend in MJO activity based on different MJO indices.

To identify whether the observed multidecadal variability of the MJO, seen in Fig. 6a, is related to any known physical modes of multidecadal variability, we examined its relationship with indices of the Pacific decadal oscillation (Minobe 1997; Latif and Barnett 1996; Mantua et al. 1997) and Atlantic multidecadal oscillation (Kerr 2000; Enfield et al. 2001). The observed multidecadal oscillation of the MJO as seen in Fig. 6a does not seem to be related to either of these oscillations. Thus, the multidecadal variability of the MJO appears to be driven internally. Even though the MJO variability and net kinetic energy exchange between the zonal mean flow and waves exhibits some physical connection, it is not clear what exactly drives the multidecadal or longer time-scale variability of the MJO or what causes the net kinetic energy exchange between the zonal mean flow and waves to show multidecadal variability. The loss of significance in MJO activity has cast a shadow over the prospects of the potential predictability of weather in the tropics and our ability to make useful extended-range prediction of the active/break spells 20–30 days ahead.
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