On the predictability of the interannual behaviour of the Madden–Julian Oscillation and its relationship with El Niño

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\textbf{Summary}

The Madden–Julian Oscillation (MJO) is the dominant mode of tropical variability at intraseasonal timescales. It displays substantial interannual variability in intensity which may have important implications for the predictability of the coupled system. The reasons for this interannual variability are not understood. The aim of this paper is to investigate whether the interannual behaviour of the MJO is related to tropical sea surface temperature (SST) anomalies, particularly El Niño, and hence whether it is predictable.

The interannual behaviour of the MJO has been diagnosed initially in the 40-year National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis. The results suggest that prior to the mid-1970s the activity of the MJO was consistently lower than during the latter part of the record. This may be related either to inadequacies in the data coverage, particularly over the tropical Indian Ocean prior to the introduction of satellite observations, or to the real effects of a decadal time-scale warming in the tropical SSTs. The teleconnection patterns between interannual variations in MJO activity and SST show only a weak, barely significant, influence of El Niño in which the MJO is more active during the cold phase.

As well as the NCEP/NCAR Reanalysis, a 4-member ensemble of 45-year integrations with the Hadley Centre climate model (HadAM2a), forced by observed SSTs for 1949–93, has been used to investigate the relationship between MJO activity and SST. HadAM2a is known to give a reasonable simulation of the MJO, and the extended record provided by this ensemble of integrations allows a more robust investigation of the predictability of MJO activity than was possible with the 40-year NCEP/NCAR Reanalysis. The results have shown that, for the decadal and interannual changes, with the atmosphere being driven by imposed SSTs, there is no reproducibility of the activity of the MJO from year-to-year. The interannual behaviour of the MJO is not controlled by the phase of El Niño and would appear to be mainly chaotic in character. However, the model results have confirmed the low-frequency, decadal time-scale variability of MJO activity seen in the NCEP/NCAR Reanalysis. The activity of the MJO is consistently lower in all realizations prior to the mid-1970s, suggesting that the MJO may become more active as tropical SSTs increase. This result may have implications for the effects of global warming on the coupled tropical atmosphere–ocean system.

Since the observed and simulated MJOs display clear seasonality in their occurrence, the relationship with interannual changes in the mean seasonal cycle of the tropical circulation has also been investigated. In contrast to the MJO, the interannual variability in the mean seasonal cycle is reproducible and influenced by the phase of El Niño. The implications of these results for the predictability of the tropical atmosphere–ocean system are discussed, particularly with reference to the strong El Niño event of 1997 which developed in association with a period of intense MJO activity.

\textbf{Keywords:} El Niño \hspace{0.5cm} Intraseasonal variability \hspace{0.5cm} Predictability

1. Introduction

The intraseasonal or Madden–Julian Oscillation (MJO) is the dominant mode of variability in the tropics at time-scales in excess of one week but less than one season. When it is active it represents a substantial modulation of the convective activity over the Indian and west Pacific Oceans. In the last decade many studies of its structure have been made using satellite data and Numerical Weather Prediction (NWP) analyses and the basic characteristics of the MJO are now well documented. Since the oscillation has such

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a large effect on the tropical diabatic heating distribution, it is not surprising that it also manifests itself in the extratropics (e.g. Ferranti et al. 1990). It has also been associated with fluctuations in the equatorial zonal flow and in the atmospheric angular momentum (e.g. Weickmann et al. 1992).

The MJO is not an ubiquitous feature of the tropical circulation. It displays a strong seasonality (e.g. Madden and Julian 1994), and substantial interannual variability in intensity (e.g. Salby and Hendon 1994). This sporadic behaviour of the MJO from year to year has not been widely studied and no reasonable explanation yet exists. The possibility that it might be linked to El Niño has been considered, but apart from the suggestion by Kousky and Kayano (1994) and Slingo et al. (1996) that the oscillation tends to be less active in El Niño years, any relationship appears to be rather tenuous. The aim of the research described in this paper is to investigate whether the interannual behaviour of the MJO is related to tropical sea surface temperature (SST) anomalies, particularly El Niño, and hence whether it is predictable.

The MJO tends to be most active during northern winter and spring, and it is in this period when it also shows its most coherent eastward propagation with its characteristic Kelvin–Rossby wave structure (Matthews 1993). The seasonal behaviour of the MJO has been explained by Salby et al. (1994) in terms of the response of the atmosphere to the latitudinal position of the tropical heat sources. They note that greatest amplification of the equatorial Kelvin wave and associated subtropical Rossby gyres occurs when the atmospheric heating is strongest at the equator, and that this happens preferentially during the vernal equinox when the SST maximum is on the equator over the entire eastern hemisphere. Thus the seasonality in the behaviour of the MJO suggests an important role for the boundary forcing (i.e. SST) in determining the structure and strength of the oscillation.

However, despite its well defined seasonality, the MJO displays substantial interannual variability in its behaviour. Some years it is very strong and coherent, in others it appears to be completely lacking. It is important to achieve an understanding of what controls this interannual variability in the intensity of the MJO, for a variety of reasons. Several factors have been suggested which might affect the behaviour of the oscillation, such as the vertical shear of the zonal wind and the horizontal and vertical distribution of diabatic heating (e.g. Lim et al. 1991; Bladé and Hartmann 1993; Lau et al. 1988). The major forcing on the mean state of the tropics is SST, its distribution, and changes in its distribution (Philander 1990); but, is the interannual variability in the activity of the MJO related to changes in the mean state of the tropics and therefore to SST, as seems to be the case for seasonality of the MJO, or is it purely stochastic and therefore inherently unpredictable?

This is an important question because the degree of predictability of the MJO’s interannual behaviour is likely to have wide-ranging implications. As the dominant mode of tropical intraseasonal variability, the activity of the MJO is likely to play an important role in seasonal prediction. Ferranti et al. (1990) provided convincing evidence that an improved representation of the MJO in the tropics of the European Centre for Medium-Range Weather Forecasts (ECMWF) forecast model (achieved in this case by relaxing the tropical circulation back towards analyses) could lead to a considerable increase in forecast skill for the extratropics in the medium term. Whether this impact can also be achieved in ensemble seasonal prediction is an important question; the answer depends on whether the activity of the MJO is related to the boundary forcing and therefore is, in some sense, predictable.

Seasonal prediction also relies on an accurate forecast of the future state of El Niño. The potential link between El Niño and the MJO has been noted by Lau and Chan (1988);
more recently Kessler and McPhaden (1995) have suggested that intraseasonal oceanic Kelvin waves, possibly excited by the MJO (Kessler et al. 1995), played a prominent part in the prolonged warm event of the early 1990s. Hendon and Glick (1997) postulated that these ocean Kelvin waves are near-resonantly forced by the eastward moving wind stress anomalies associated with the MJO, and can themselves give rise to SST anomalies in the east and central Pacific of the order of 0.25 K. The relationship between ocean Kelvin waves and the MJO has been analysed further by Hendon et al. (1998) who concluded that the large spatial scale of the zonal wind stress anomalies produced by the MJO and the near-resonant forcing west of the date line can reconcile the discrepancy in the periodicities of the ocean Kelvin waves (~70 days) and the MJO (40–50 days).

Intense near-surface westerly wind events over the tropical Pacific Ocean, known as Westernly Wind Bursts (WWBs), are often related to the active phase of the MJO (e.g. Kiladis et al. 1994). Various studies have suggested that WWBs have a direct effect on the ocean through the initiation of a downwelling Kelvin wave (e.g. Kindle and Phoebus 1995). Preliminary results from a study of ECMWF Reanalysis suggest that WWBs tend to be more prevalent in years with strong MJO activity, in agreement with earlier studies of, for example, Nakazawa (1988). The impact of this interannual variability in MJO and WWB activity on the ocean is likely to be important and thus the role that the MJO plays in the evolution of El Niño may be significant. This point will be discussed further in section 6 with respect to the strong El Niño that developed during the early months of 1997.

If the activity of the MJO is controlled in some way by SST, then changes in SST, due to anthropogenic or natural perturbations to the climate, may alter the nature and intensity of the MJO. This itself would constitute an important change in the transient characteristics of the tropical climate, affecting intraseasonal and interannual time-scales and potentially including, as noted above, an influence on the behaviour of El Niño.

Clearly all these arguments point towards the importance of understanding the link between SST and the activity of the MJO. This requires an objective method for quantifying the activity of the MJO from year to year which properly identifies a coherent, eastward propagating intraseasonal mode which has a global structure and is distinct from other more local intraseasonal behaviour. In this paper, satellite observations and the 40-year National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis have been used, firstly, to investigate the observed interannual variability of the MJO and secondly, to identify a suitable index which describes the activity of the MJO and which can also be applied to model results. The results of a 4-member ensemble of 45-year integrations of the Hadley Centre climate model, forced with observed SSTs for the period 1949–1993, have then been used to assess the reproducibility of MJO activity from year to year and to investigate whether there is a predictable relationship with SST. Since an atmosphere-only model is being used, this study cannot address the question of the influence of variations in the MJO activity on the variability of the ocean, particularly El Niño.

A brief description of the satellite observations and the NCEP/NCAR Reanalysis, used to identify the observed characteristics of the interannual variability in the MJO, is given in section 2. The observed interannual behaviour of the MJO is documented in section 3, from which an index to describe MJO activity is proposed and used subsequently in the diagnosis of the model results. The version of the Hadley Centre climate model used in this paper is described briefly in section 4; details of the SSTs used to force the model are also given. The results from the ensemble of integrations with the model are presented in section 5. The implications of the results are discussed in section 6 where their relevance to the El Niño event of 1997 is also considered.
2. DESCRIPTION OF THE NCEP/NCAR REANALYSIS AND THE SATELLITE DATA

The NCEP/NCAR Reanalysis Project is a joint project between NCEP and NCAR to produce a 40-year record of global atmospheric analyses with a data assimilation system that is unchanged. A full description of the project is given in Kalnay et al. (1996). The data assimilation and forecast model were based on the global system which was implemented operationally at NCEP in January 1995. The model was run at a horizontal (spectral) resolution of T62 (i.e. triangular truncation at 62 wave numbers) and with 28 vertical levels. The observational database has been considerably increased with many sources of data that were not available in real time.

Data were assimilated using a spectral statistical interpolation/3-D variational analysis method which requires no nonlinear normal mode initialization. Daily mean upper air data on standard pressure surfaces were available, already gridded on to a 2.5° latitude/longitude grid. In this paper the Reanalysis for the period 1958–97 has been used.

As well as the Reanalysis, outgoing long-wave radiation (OLR) from the Advanced Very High-Resolution Radiometer (AVHRR) on the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites has been used to identify the convective signature of the MJO. These data have been daily averaged and have been processed on to a 2.5° latitude/longitude grid with missing values filled by interpolation (Liebmann and Smith 1996). This data set has already been used in a variety of studies (e.g. Salby and Hendon 1994) and is a reasonable proxy for tropical convective activity (Arkin and Ardanuy 1989). In this paper the continuous record from 1979 to 1997 has been used to identify the MJO.

To isolate the MJO, the satellite and Reanalysis daily data have been band-pass filtered with a 20–100 day 100-point Lanczos filter, as used in Slingo et al. (1996).

3. THE MJO AND ITS INTERANNUAL BEHAVIOUR IN THE 40-YEAR NCEP/NCAR REANALYSIS

(a) Description of the dominant modes and definition of an MJO activity index

The MJO produces a substantial modulation of tropical convection which is readily apparent in satellite data (e.g. Murakami et al. 1986). Figure 1(a) shows the dominant modes of intraseasonal variability in the observed daily 20–100 day filtered OLR data for 1979–97, as described by Empirical Orthogonal Function (EOF) analysis. These two modes (EOF1 and EOF2) basically describe the convective maxima over the Indian Ocean and West Pacific associated with the active phase of the MJO. The time series of the first two principal components (PC1 and PC2; Fig. 1(b)) indicate eastwards propagation with PC1 typically leading PC2 by about 10 days. The dominant patterns are very similar to those obtained by Zhang and Hendon (1997) when they considered the propagating rather than the stationary component of intraseasonal activity.

The seasonal and interannual variability in the convective activity of the MJO is evident in the time series of the two dominant PCs (Fig. 1(b)). When the MJO is active, not only are the amplitudes of the PCs large, but there is also a coherent, characteristic time-lag between PC1 and PC2 as noted above. For example, the MJO was very active during the early months of 1988 and 1990 during which time it made several circuits of the globe. This clustering of MJO events is typical of its behaviour when the oscillation is active. At other times, such as during 1986 and 1987, the amplitude of one PC can be quite large but there is no coherent relationship between the PCs, suggesting that the convection during this type of intraseasonal variability is localized and not representative of the coherent eastward propagating behaviour of the MJO. It is important to note here that the behaviour of the
Figure 1. (a) Dominant modes of the intraseasonal variability in the band-pass (20–100 days) filtered daily outgoing long-wave radiation (OLR) measured by the AVHRR for 1979–97. EOF1 and EOF2 explain 13% and 9% of the variance, respectively. Negative contours (i.e. enhanced convection) are dashed, positive contours are solid and the zero contour is dotted. (b) Example of the time series of the principal components, PC1 (solid) and PC2 (dashed), of the dominant modes. (See text for further information.)
PCs in Fig. 1 shows that the largest modulation of the OLR at intraseasonal time-scales is associated with MJO events rather than other types of intraseasonal variability. Therefore it is essential to distinguish MJO-related variability from other types and to effectively isolate the seasonal and interannual characteristics of MJO activity.

Although the years with an active MJO can be identified subjectively from PC time series of the type shown in Fig. 1, a quantitative measure is more difficult to find. Slingo et al. (1996), in their study of the MJO simulated by 15 models in the Atmospheric Model Intercomparison Project (AMIP), introduced the modulation of the upper-tropospheric equatorial zonal mean of the zonal wind (u) as a measure of the activity of the MJO at seasonal to interannual time-scales. They postulated that changes in [u] represented a synthesis of how intraseasonal variability in the atmospheric diabatic heating translated into modification of the planetary-scale circulation patterns.

In the tropics, the upper-tropospheric zonal flow is predominantly easterly, but with some important seasonal variations, such as the stronger northern summer monsoon easterlies in the eastern hemisphere, and the winter westerlies of the Pacific and Atlantic wave guides in the western hemisphere. These seasonal changes are sufficiently large that [u] for the equatorial belt varies from mean westerlies in northern winter to mean easterlies in northern summer. This can be seen in Fig. 2 where the evolution of [u] at 200 hPa, averaged between 10°N and 10°S, has been plotted using daily mean data from the NCEP/NCAR Reanalysis for the years 1979–97. The seasonal and intraseasonal characteristics of [u] have been identified by filtering the data with low-pass (>100 days) and band-pass (20–100 days) filters. The total field shows a well defined seasonal cycle with intraseasonal variations superimposed on it. Considerable interannual variability in the seasonal cycle is evident in the low-pass filtered data. It is reassuring that many aspects of Fig. 2 are similar to the diagnosis of the earlier ECMWF Analyses by the Joint Diagnostics Project (JDP) (Hoskins et al. 1989) and shown in Fig. 11 of Slingo et al. (1996).

As the lower panel of Fig. 2 shows, the intraseasonal variations in [u] are of the order of ±2 m s⁻¹, but with considerable variation in intensity. There are clear periods where the amplitude is higher and the oscillations are more regular in character (e.g. 1981, 1988 and 1990). In Fig. 3, the variance of the band-pass (20–100 days) filtered [u] from Fig. 2 (lower panel) has been computed and then plotted within a 100-day moving window. As in Fig. 14 from Slingo et al. (1996), this essentially shows how the intraseasonal activity is modulated at lower frequencies associated with seasonal and interannual time-scales. Also shown in Fig. 3 are the SST anomalies for the Niño3 (5°N–5°S, 150°W–150°E) region of the central and east Pacific. Again the similarity between the results from the NCEP/NCAR Reanalysis (Fig. 3) and from the operational ECMWF Analyses (Fig. 14 of Slingo et al. 1996) is reassuring.

Comparison of Fig. 3 with the PC time series shown in Fig. 1, suggests that the variance of the band-pass filtered [u] clearly delineates the periods of strong MJO activity from those with other more local intraseasonal behaviour. The preference for the MJO to form during northern winter and spring is clearly evident in Fig. 3. The strong MJO activity during the early months of 1997 is also evident. Slingo et al. (1996) noted that the results for the AMIP decade (1979–88) suggested that the oscillation tends to be suppressed during the warm phase of El Niño. However, they also noted that the relationship is far from robust with such a limited sample and may well require an extended reanalysis data set and/or long model integrations to provide firm evidence of any relationship between MJO activity and SST forcing. Consequently the behaviour of the MJO in the 40-year NCEP/NCAR Reanalysis has been investigated.

The dominant modes of intraseasonal variability in the 20–100 day band-pass filtered velocity potential (χ) and eddy stream function (ψ*) at 200 hPa from the NCEP/NCAR
Figure 2. Time series of the upper tropospheric zonal mean of the zonal wind ($[u] \text{ m s}^{-1}$) averaged between $10^\circ\text{N}$ and $10^\circ\text{S}$ from NCEP/NCAR Reanalysis for 1979–97. Upper panel: total $[u]$, thin line; low-pass filtered $[u]$ thick line. Lower panel: band-pass filtered $[u]$ (20–100 days).

Figure 3. Interannual variability in the activity of the MJO as depicted by the time series of the variance ($\text{m}^2\text{s}^{-2}$) of the band-pass filtered $[u]$ as shown in Fig. 2 (lower panel) from the NCEP/NCAR Reanalysis for 1979–97. A 100-day running mean has been applied to the variance time series. The lower, shaded curve is the sea surface temperature anomaly (K) for the Niño3 region ($5^\circ\text{N}–5^\circ\text{S}, 90^\circ\text{W}–150^\circ\text{W}$). (See text for further information.)
Reanalysis for 1958–97 are shown in Fig. 4. These again basically describe the main centres of action of the MJO over the Indian Ocean and Indonesian/west Pacific domains, although in comparison with the results from the satellite OLR data (Fig. 1), EOF1 and EOF2 are reversed. PC1(2) of velocity potential from the NCEP/NCAR Reanalysis is well correlated (>0.7) at zero lag with PC2(1) of OLR from AVHRR satellite data (Fig. 1). The eddy stream function shows the characteristic development of the forced Rossby modes associated with the active phase of the MJO, in which twin cyclones form to the east and twin anticyclones to the west of the main area of heating, i.e. divergence in the velocity-potential field. The first PCs of velocity potential and eddy stream function are highly correlated (>0.9) at zero lag, confirming the coupled Kelvin–Rossby wave structure found in other studies based on shorter-period data sets (e.g. Rui and Wang 1990). As with the OLR observations (Fig. 1), the PC time series show eastward propagation in which PC2 leads PC1 by approximately 10 days for both velocity potential and eddy stream function. The lag correlation coefficients between PC1 and PC2 peak at 0.72 and 0.65 for velocity potential and eddy stream function, respectively.

As noted earlier, the MJO influences $\{u\}$, and hence the angular momentum and length of day (e.g. Magaña 1993). In a study of the MJO in ECMWF analyses, Matthews (1993) diagnosed the dominant mode of the zonal part of the stream function and found that it essentially describes a modulation of the equatorial zonal mean winds which is coherent with the active phases of the MJO. Figure 5 shows the first two EOFs of the band-pass filtered zonal stream function $(\{\psi\})$ from the NCEP/NCAR 40-year Reanalysis, expressed here in the more convenient form as the rotational part of the zonal mean of the zonal wind $(\{u\}_x = -d\{\psi\}/dy)$. EOF1 basically describes a coincident intensification of the equatorial easterlies and subtropical westerly jets, whereas EOF2 describes a reversal of the equatorial anomalies but a polewards shift of the subtropical jets. The PCs of $\{u\}_x$ show that PC1 leads PC2 by 10–15 days with a lag correlation of ~0.4. PC1 of $\{u\}_x$ has its maximum correlation (0.36) with PC2 of $\chi$ at zero lag implying that easterly anomalies in the zonal mean rotational flow are coincident with the active phase of the MJO over the Indian Ocean. Similarly, westerly anomalies in $\{u\}_x$ are associated with enhanced convection over the west and central Pacific. Matthews (1993) found the same relationship in his diagnosis of ECMWF analyses for the period 1982–90. Returning to the band-pass filtered $\{u\}$ which was used by Slingo et al. (1996) to describe the seasonal and interannual variations in MJO activity (Fig. 3), the correlation between the band-pass filtered $\{u\}$ and the first PC of $\{u\}_x$ is very high (0.86) at zero lag, confirming that the band-pass filtered $\{u\}$ describes the dominant behaviour of the MJO.

Potentially there are various indices that could be used to quantify MJO activity based on the behaviour of the dominant modes of intraseasonal activity. For example, Zhang (1997) used the expansion coefficient of the first mode from a Singular Value Decomposition (SVD) analysis of OLR and 850 hPa zonal wind. This is equivalent to using the PC time series of the dominant modes from an EOF analysis to describe the activity of the MJO. In Fig. 6, various measures of MJO activity are compared, based on the variance of PC1 for $\chi$, $\psi^*$ and $\{\psi\}$ within a 100-day moving window, for the period 1979–97, coincident with that used in Figs. 1–3. As expected, the index based on PC1($\{\psi\}$) is very close to that based on band-pass filtered $\{u\}$ (Fig. 3), whereas those based on more regional characteristics (PC1($\chi$) and PC1($\psi^*$)) suggest overall more MJO activity.

Although there is no clear indication from the above analysis which measure of MJO activity is preferable, the use of the band-pass filtered $\{u\}$ to describe the activity of the MJO appears to delineate the periods of high MJO activity (as suggested by the coherent variations in PC1 and PC2 of OLR shown in Fig. 1) more successfully than the other more regionally PC-based indices. As an index of MJO activity it is also appealing because it
Dominant modes (EOF1 and EOF2) of the interseasonal variability in the band-pass (20–100 days) filtered 200 hPa velocity potential (\(\psi\)) and eddy stream function (\(\psi^*\)) from the NCEP/NCAR Reanalysis for 1979–97. Positive contours are solid, negative contours are dashed, and the zero contour is dotted. See text for further information.
is not the result of an EOF analysis, but is the direct response of the zonal mean flow to forcing by the MJO. The fact that it is highly correlated with the rotational part of the zonal mean flow confirms that it is closely linked to the forced Rossby mode structure of the MJO rather than to other types of intraseasonal variability. The hypothesis presented in Slingo et al. (1996) that the band-pass filtered $[u]$ represents a synthesis of the response of the planetary-scale circulation to MJO activity is supported by the diagnosis of dominant modes of MJO behaviour in the NCEP/NCAR Reanalysis presented here. In addition, the use of $[u]$ is appealing for diagnosing extended model integrations because the amount of data manipulation is considerably less than that involved in EOF analysis.

(b) Decadal changes in MJO activity

Taking the MJO index based on the band-pass filtered $[u]$, the relationship between MJO activity and low-frequency boundary forcing (e.g. SST) can be investigated using the 40-year record from the NCEP/NCAR Reanalysis. The data set should be of sufficient length to give a fairly robust signal. However, when the MJO index was computed for the full record (Fig. 7), it became clear that there was a marked change in the character of the MJO activity prior to the mid-1970s with no periods of strong activity comparable to those observed during the 1980s and 1990s. In terms of the time mean of the MJO index, which describes the overall level of intraseasonal activity, the value for 1958–76 was 2.05 whilst for 1977–96 it was 2.40.

There appear to be two possible reasons for this apparent change in the activity of the MJO. The first is that this does not represent a real change; instead, in data-sparse regions of the tropics, the increased observational database with the introduction of satellite winds in the late 1970s has enabled a better analysis of the MJO. Although the patterns of dominant modes are almost identical when the EOF analysis was performed on the full (1958–97), the early (1958–78) or the latter portion (1979–97) of the record, suggesting that the structure of the MJO is stationary throughout the record, the temporal characteristics of the dominant modes of $\chi$ and $\psi^*$ have changed. The amplitude of PC1 (which essentially corresponds to intraseasonal activity in the west Pacific) is consistent in magnitude throughout the 40-year record. However, PC2 (which describes intraseasonal activity in the Indian Ocean) shows a systematic drop in amplitude prior to around 1975. The tropical Indian Ocean has very few observing stations compared with the west Pacific; therefore the analysis in that
Figure 6. Comparison of measures of MJO activity based on the variance of (a) PC1 of 200 hPa velocity potential ($\chi$), (b) PC1 of 200 hPa eddy stream function ($\psi^*$), and (c) variance of PC1 of 200 hPa zonal stream function ([$\psi$]) from NCEP/NCAR Reanalysis. A 100-day running mean has been applied to the variance time series. As in Fig. 3, the lower, shaded curve in all panels is the sea surface temperature anomaly (K) for the Niño3 region. (See text for further information.)
region is likely to be very sensitive to the introduction of satellite winds. Thus, although the Reanalysis is based on a consistent data assimilation, analysis and forecast system, and also includes additional data (e.g. satellite measurements, field experiments) which were not available operationally, the overall lack of observations in some regions of the globe cannot be overcome.

The second possible reason for the change in activity of the MJO suggests that it may be real. Tropical SSTs display a low-frequency, decadal time-scale variability which is captured by the dominant EOF (explaining 28% of the variance) of the monthly mean SSTs (after removal of the mean seasonal cycle), as used in the NCEP/NCAR Reanalysis for the region of the tropics where the MJO is convectively active (i.e. 60°E–180°E; Fig. 8(a)). During the latter part of the 1970s there was an abrupt change from a predominantly negative PC1 (i.e. colder Indian Ocean) to a positive PC1 (i.e. warmer Indian Ocean; Fig. 8(b)), indicative of a general warming of the tropical Indian Ocean by at least 0.5 K over the last 40 years. The sudden, interdecadal change around 1977 in the characteristics of the atmospheric circulation and SST, particularly related to El Niño Southern Oscillation, has been widely documented (e.g. Wang 1995; Zhang et al. 1997) and is evident also in Fig. 8 for the SSTs of the Indian Ocean and Maritime Continent. The change in intraseasonal activity around the mid-1970s in the NCEP/NCAR Reanalysis, particularly over the Indian Ocean, may be related to the warmer SSTs in the Indian Ocean during the latter part of the record.

At this stage it is not possible to conclude which of these two reasons provides the explanation for the decadal time-scale variations in MJO activity seen in the NCEP/NCAR Reanalysis. However, results from an ensemble of integrations with the Hadley Centre climate model, described in section 5, support the idea that decadal variations of SST may be influential.

(c) Interannual variability in MJO activity and its teleconnections with SST

If the decadal variability described in Fig. 7 is real, and not an artifact of changes in the observational database, then it is reasonable to investigate the teleconnections between
SST and changes in the activity of the MJO from year to year. Remembering that the MJO displays considerable seasonality in its behaviour, being most active during the early months of the year, the mean MJO index for January to April has been computed, and the instantaneous correlation patterns with the global SSTs averaged for the same months have been produced (Fig. 9). The upper panel in Fig. 9 shows the teleconnection pattern for the whole record (1959–97) whereas the lower panel shows the pattern for the more recent period when the MJO appears to have been more active (1977–97). For the Pacific Ocean, both periods show an El Niño-type relationship with more MJO activity during cold phases, but in neither case are the negative correlations significant except for a small area in the central Pacific. Only in the west Pacific are the positive correlations marginally significant. The patterns for the Indian Ocean are more variable and depend on the years chosen for analysis. (Note also that similar patterns were obtained using other measures of MJO activity, such as PC1 of \( \chi \), as discussed in section 3(a)). Fink and Speth (1997) also found no clear relationship between El Niño and the convective signal associated with MJO activity, except for longitudes east of 160°E where the extension of the mean convection eastwards also gives rise to a signal at intraseasonal time-scales. For the eastern Indian Ocean and the west Pacific, Fink and Speth (1997) found no evidence that interannual variations in SST systematically modify the seasonal MJO activity.
In summary, the study of the MJO in the 40-year NCEP/NCAR Reanalysis has confirmed the characteristic coupled Kelvin–Rossby wave structure of the oscillation seen in shorter records. It has also demonstrated that the MJO projects on to the zonal mean flow primarily through the rotational component of the flow. The modulation of the zonal mean flow can be related to the eastward propagation of the active phase of the MJO from the Indian Ocean into the west and central Pacific. There appear to be systematic trends in the activity of the MJO in the 40-year NCEP/NCAR Reanalysis which may be associated with interdecadal variations in the atmospheric circulation and SST. At interannual time-scales, however, no statistically significant relationship between MJO activity and SST has been found. This may be because the record is still rather short to find a predictable signal. Consequently the question of the predictability of the interannual behaviour of the MJO has been investigated further using a 4-member ensemble of 45-year integrations with the Hadley Centre climate model forced with observed SSTs for 1949–93.

4. DESCRIPTION OF THE MODEL AND INTEGRATIONS

The model used in this study is the Hadley Centre climate model, version HadAM2a, a configuration of the United Kingdom Meteorological Office (UKMO) Unified Model. Its resolution is 2.5° latitude by 3.75° longitude with 19 levels in the vertical. It was developed from HadAM1, the UKMO’s first model submitted to the Atmospheric Model Intercomparison Project (AMIP described by Phillips 1994), incorporating improvements to the cloud and precipitation schemes, some tuning of horizontal diffusion, and minor corrections to the albedo and ozone files.
The model includes the following physical parametrizations:

- a gravity wave drag scheme;
- a radiation scheme which computes fluxes in four long-wave bands and six short-wave bands, and responds to prognostic cloud variables (large-scale cloud amount, cloud liquid water and ice content, and convective cloud amount);
- a penetrative convection scheme with stability dependent closure, which represents both updraughts and downdraughts;
- boundary layer mixing in up to five of the lowest model layers;
- a land surface scheme which includes a vegetation canopy model, a four-layer soil model for heat conduction, and a single-layer soil model for moisture storage including surface and sub-surface runoff.

The model’s chemistry involves seasonally and meridionally varying ozone profiles, and a fixed carbon dioxide concentration (321 parts per million by volume (p.p.m.v.)).

In their analysis of the performance of 15 atmospheric General Circulation Models (GCMs) as part of AMIP, Slingo et al. (1996) identified HadAM1 as a model that simulated one of the most realistic MJOs. Subsequently, Sperber et al. (1997) completed a more detailed study of the model’s MJO and compared it with a similar diagnosis of NCEP/NCAR Reanalysis. They showed that the characteristic Rossby–Kelvin wave structure of the MJO was well simulated by the model, but that the eastward propagating signature in the convection was more irregular in the model than observed. Similar results have been obtained in a diagnosis of the MJO simulated by HadAM2b in an extended perpetual March integration (Matthews et al. 1999). The characteristics of the MJO simulated by HadAM2a, the version of the model used in this paper, are consistent with those in HadAM1 and HadAM2b, and hence will not be described in detail here.

Four integrations have been carried out whilst applying a version of the Hadley Centre Global sea-Ice and Sea Surface Temperature (GISST1.1) data set as a boundary forcing for the period October 1948 to December 1993. The integrations differed only in their initial conditions. For the purpose of this study a 4-member ensemble of data sets was available for the 45-year period January 1949 to December 1993.

The GISST1.1 data set, described by Parker et al. (1995), was primarily designed to force climate models, and so is necessarily globally complete. This was achieved using a Laplacian blend of spatially incomplete MOHSSST5 anomalies (Meteorological Office Historical Sea Surface Temperature data set) with a globally complete 1951–80 climatology (Bottomley et al. 1990). Satellite estimates of SST were utilized from 1982, and sea-ice extents since 1973 were taken from NOAA; prior to that a variety of sources, often climatologies, were used. Although the nominal resolution of GISST1.1 is about 5°, the data are available on a 1° grid; these were then interpolated to the model grid, and also interpolated from monthly means to 5-day means.

5. MJO ACTIVITY IN THE HADLEY CENTRE CLIMATE MODEL FORCED WITH OBSERVED SSTS

(a) Reproducibility of interannual changes in MJO activity

The reproducibility of interannual variations in the activity of the simulated MJO has been assessed in terms of the temporal characteristics of the band-pass (20–100 days) filtered zonal mean of the zonal wind, [u], as described for the NCEP/NCAR Reanalysis. The advantage of this approach is that a potentially large amount of data can be reduced to a feasible level without obscuring the important results. Figure 10 shows a typical example of the evolution of [u] at 200 hPa, averaged between 10°N and 10°S, for the years 1979–93
from one realization with HadAM2a. These 15 years are shown to facilitate comparison with the results from the NCEP/NCAR Reanalysis (Fig. 2). As in Fig. 2, the seasonal and intraseasonal characteristics of $|u|$ have been identified by filtering the data with low-pass (>100 days) and band-pass (20–100 days) filters.

As in the earlier results from HadAM1 for AMIP (see Fig. 11 of Slingo et al. 1996), HadAM2a has simulated a well-defined seasonal cycle with mean westerlies during northern winter and easterlies in summer. The amplitude of the seasonal cycle is stronger (4.59 m s$^{-1}$) than in the NCEP/NCAR Reanalysis (3.22 m s$^{-1}$) and the model has failed to capture as consistently the double maxima in the westerlies during northern winter and spring. The Asian summer monsoon is systematically too strong in HadAM2a and this is reflected in the upper tropospheric mean easterlies which are more intense than in the NCEP/NCAR Reanalysis. The model has simulated marked interannual variability in the behaviour of the seasonal cycle, an aspect of the results which will be discussed further in section 5(c).

In Fig. 10, strong intraseasonal variations in $|u|$ are clearly evident. Their amplitude is close to that seen in the NCEP/NCAR Reanalysis (Fig. 2). The mean amplitude for all realizations is 1.10 m s$^{-1}$ compared with 1.19 m s$^{-1}$ in the Reanalysis. (Note that Slingo et al. (1996) reported 1.23 m s$^{-1}$ for the ECMWF analyses for the shorter period 1982–90). The model result suggests that the intraseasonal variations are realistically weaker in this
version of the Hadley Centre climate model than in that used for AMIP where the mean amplitude was 1.81 m s\(^{-1}\).

Using the variance of the band-pass filtered [u] to identify interannual variability in the activity of the MJO, as described earlier for the NCEP/NCAR Reanalysis (Figs. 3 and 7), the behaviour of the 4 realizations is summarized in Fig. 11. This index of MJO activity shows that all the realizations contain a few years when the oscillation is particularly active, but that there is no agreement between the realizations for the years involved. The reproducibility of the MJO index for the four realizations has been measured using the analysis of variance method, (ANOVA; Rowell et al. 1995; Rowell 1998). The calculation essentially estimates the percentage of the variance which is the same in the four time series. In this case only 10% of the variance was found to be the same in each of the integrations and, therefore, only 10% of the total variance can be attributed to the external, boundary forcing, i.e. SST. The other 90% is due to internal variability. This is the key result of the paper. For the uncoupled system, with the atmosphere being driven by imposed SSTs, there is no reproducibility for the activity of the MJO from year to year.

Using the results shown in Fig. 11, the teleconnection patterns between the seasonal mean MJO index for January to April and the SST distributions have been computed (Fig. 12) as for the NCEP/NCAR Reanalysis (Fig. 9). The upper panel of Fig. 12 shows the pattern for all winters (1950–93), whereas the lower panel shows the pattern for the latter part of the record, 1977–93. Globally the correlations are small, generally below the level of significance. In comparison with the teleconnection patterns computed for the NCEP/NCAR Reanalysis (Fig. 9), the model results again suggest a marginally significant correlation with higher than normal SSTs in the west Pacific. The relationship with El Niño is not significant, and has the opposite sign to that suggested by the NCEP/NCAR Reanalysis, i.e. more MJO activity during the warm phase of El Niño.

The results confirm those from ANOVA and show that, for the model at least, the interannual behaviour of the MJO is not controlled by the phase of El Niño or by any other SST pattern. This suggests that the activity of the MJO from year to year would appear to be chaotic in character. This result is perhaps not surprising when seen in the context of the behaviour of the MJO in integrations with either climatological SSTs or fixed-season forcing (i.e. perpetual mode). Slingo and Madden (1991) noted the sporadic behaviour of the MJO in a perpetual January integration of the NCAR Community Climate Model (CCM1). Similarly Matthews et al. (1999), in their analysis of the MJO in a 1800-day perpetual March integration of the Hadley Centre climate model (HadAM2b), found that the MJO was sometimes very active, making several circuits of the globe, and sometimes completely lacking. These results confirm that the intermittent behaviour of the MJO can be internally generated without any temporal variations in the boundary forcing.

(b) Reproducibility of decadal changes in MJO activity

An intriguing aspect of the results from the NCEP/NCAR Reanalysis was the apparent change in the level of intraseasonal activity in the late 1970s (Fig. 7) which might be related to interdecadal changes in tropical SSTs (Fig. 8). An EOF analysis of the GISST 1.1 SSTs, used to force the model, shows a very similar pattern for the dominant EOF (explaining 21% of the variance), with PC1 again displaying an abrupt change from predominantly colder to warmer conditions in the late 1970s (Fig. 13).

The behaviour of the simulated MJO in Fig. 11 suggests that the model has reproduced the change in MJO activity seen in the NCEP/NCAR Reanalysis, with the MJO being consistently less active in the earlier part of the record. This has been quantified in Table 1 where the mean MJO activity (using the MJO index shown in Figs. 7 and 11) for all months has been computed for the complete years prior to and following 1977. For comparison
Figure 11. Interannual variability in the activity of the Madden–Julian Oscillation (MJO) as simulated by each member of the ensemble of model integrations. As in Fig. 7, the variance of the band-pass filtered [u] is used with a 100-day running mean applied. (See text for further information.)
Figure 12. Teleconnection patterns of the seasonal mean (January–April) MJO index with sea surface temperature for the whole period 1950–92 (upper panel) and for the latter part of the record 1977–92 (lower panel) as simulated by HadAM2a. The teleconnections have been computed using results from all members of the ensemble. Correlations with absolute value greater than 0.15 are significant at the 95% confidence level for the upper panel (0.24 for the lower panel). The contour interval is 0.05 with positive contours solid, negative contours dashed, and negative values less than −0.05 shaded. (See text for further information.)

Figure 13. Time series of the principal component (PC1) of the first EOF of the seasonally detrended monthly mean sea surface temperatures for 1949–93 from GISST1.1 for the domain 20°N–20°S, 60°E–180°E. (See text for further information.)

<table>
<thead>
<tr>
<th>Realization</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>NCEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950(59)–92</td>
<td>1.80</td>
<td>1.95</td>
<td>1.91</td>
<td>1.80</td>
<td>1.75</td>
</tr>
<tr>
<td>1950(59)–76</td>
<td>1.68</td>
<td>1.81</td>
<td>1.65</td>
<td>1.67</td>
<td>1.51</td>
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<tr>
<td>1977–92</td>
<td>2.00</td>
<td>2.19</td>
<td>2.34</td>
<td>2.02</td>
<td>2.60</td>
</tr>
</tbody>
</table>

**TABLE 1.** Mean MJO index for all months, for the years shown.
with the NCEP/NCAR Reanalysis, the values given in brackets are for the complete years from 1959 onwards. The results for each realization are shown in order to demonstrate the robustness of the signal. The level of MJO activity is systematically lower prior to 1977 in all model realizations and in the NCEP/NCAR Reanalysis. This suggests that, as the tropical SSTs increase (see Figs. 8 and 13), the MJO tends to become more active. Here the focus is on the eastern hemisphere SSTs rather than the east Pacific SSTs; it is over the Indian and west Pacific Oceans where the MJO is thought to be triggered and where it has its greatest convective signal. The fact that there does not appear to be a relationship between SST and MJO activity at interannual time-scales, yet at decadal time-scales there does seem to be a relationship, is because a large part of the chaotic element has been removed by averaging over these longer time-scales.

It would be tempting to draw conclusions from the reproducibility of decadal time-scale changes in MJO activity, and its relationship with tropical SSTs, in terms of the consequences of global warming for the behaviour of the MJO. Certainly the results from the NCEP/NCAR Reanalysis and the model simulations suggest that if SSTs in the Indian and west Pacific Oceans continue to rise then MJO activity may tend to increase.

(c) Relationship between interannual changes in MJO activity and in the seasonal cycle

The observed MJO displays a marked seasonality in its occurrence, being most prevalent in northern winter and spring. Using the MJO indices shown in Figs. 7 and 11, the seasonal cycle of MJO activity has been computed for the NCEP/NCAR Reanalysis and for each realization with HadAM2a. The results confirm that the observed MJO is most active in the early months of the year with peak activity occurring in early February. This behaviour has been successfully simulated by the model, although the peak activity is slightly weaker, possibly due to the much larger sample size for the model results (172 years) compared with the NCEP/NCAR Reanalysis (38 years).

As discussed in the Introduction, it can be argued that the MJO should be most active in northern winter and spring when the SSTs and hence the diabatic heating are most symmetric about the equator (Salby et al. 1994). Slingo et al. (1996) noted the similarity between the atmospheric response to tropical heating anomalies at intraseasonal, seasonal and interannual time-scales and suggested that it may be useful to consider a model’s intraseasonal variability in the context of its seasonal behaviour. The reproducibility of the seasonal cycle in the activity of the MJO by the model suggests that, at least on the seasonal time-scale, the simulated MJO is sensitive to the basic tropical climate and hence to SST.

If the activity of the MJO is sensitive to the phase of the seasonal cycle, then its apparent lack of predictability from year to year may be because the interannual behaviour of the seasonal cycle (such as the evolution of the heating distribution and by inference [u]) is also unpredictable. Considerable interannual variability in the evolution of the seasonal cycle of [u] was noted earlier in both the NCEP/NCAR Reanalysis (Fig. 2) and in the model results (Fig. 10). The reproducibility of the seasonal cycle in the four realizations with HadAM2a has therefore been investigated using the low-pass filtered (>100 days) [u]. The ensemble mean seasonal cycle in the low-pass filtered [u] was calculated first, and then the anomalies from the ensemble mean seasonal cycle were computed for each realization (Fig. 14). The deviation of the low-pass filtered [u] from the mean seasonal cycle shows considerable interannual variability in the seasonal cycle; this can be attributed to the modulation in the strength of the maxima and minima, and also to subtle changes in the timing of the seasonal cycle, remembering that the analysis presented here has been performed on daily, not monthly mean, data.
As with the MJO index, the reproducibility of the variations in the seasonal cycle for the four realizations has been quantified using the ANOVA method. The results show that 63% of the variations in the seasonal cycle are the same in each realization. This suggests that the external, boundary forcing (i.e. SST) has a considerable influence on the evolution and amplitude of the seasonal cycle from year to year. The interannual and longer time-scale variability (e.g. associated with El Niño) in the behaviour of the seasonal cycle can be isolated by applying a 360-day (or 12-month) running mean to the time series (Fig. 15). Here the reproducibility of the model results is even more striking, a consistent low-frequency behaviour being clearly evident with the ANOVA method giving 79% of the variance attributed to the boundary forcing. A westerly trend in the zonal mean wind over the 45-year integration time is seen which also appears to be highly reproducible. Also included in Fig. 15 is the low-frequency behaviour of the low-pass filtered $[u]$ from the
NCEP/NCAR Reanalysis. This shows variations in the seasonal cycle of similar magnitude to those produced by the model, and again an indication of a change from easterly to more westerly anomalies during the period, suggesting a possible influence of the interdecadal changes in SST.

The results shown in Fig. 15 and the high percentage given by ANOVA suggests that, at least for HadAM2a integrated in uncoupled mode, the interannual variability in the evolution of the seasonal cycle (as measured in terms of [ul] is highly reproducible and hence potentially predictable. The interpretation of this result in terms of the predictability of regional changes in the seasonal heating distribution and circulation clearly merits further study, although the results of Rowell (1998) suggest that seasonal anomalies in the precipitation over the west Pacific are fairly reproducible and hence potentially predictable.

6. IMPLICATIONS OF THE RESULTS AND THEIR RELEVANCE TO THE DEVELOPMENT OF THE 1997/98 EL NIÑO

Although the central theme of this paper has been the potential predictability of the interannual behaviour of the MJO, the extension of the analysis to include the seasonal cycle has raised the interesting question of the relationship between the predictability of these different time-scales. The results described above have suggested that interannual variations in the tropical seasonal cycle may be strongly influenced by the SSTs, as also suggested by Gu and Philander (1995), yet the activity of the MJO is insensitive to the SSTs and therefore, by inference, to these variations in the seasonal cycle.

In a paper addressing the predictability of the Asian summer monsoon, Palmer (1994) presented the scenario in which intraseasonal variability is essentially chaotic but its probability distribution function (i.e. the likely occurrence of one regime rather than another) is influenced by the boundary forcing. Using the simple Lorenz model, Palmer proposed that a change in the boundary forcing, such as SST, could influence the probability of one regime of intraseasonal behaviour without affecting the structure of the regime itself. If it is the case that the probability characteristics of intraseasonal variability can be influenced by the boundary forcing, then there is potential for predictability on the seasonal to interannual time-scale. In his study, Palmer (1994) focused on the active/break cycle of the Asian summer monsoon, but his ideas could be extended to the behaviour of the MJO described in this paper. Here the results contradict the notion of intraseasonal activity being controlled by the boundary forcing, at least on the interannual time-scale. They preclude, therefore, the potential for predictability of the activity of the MJO on the seasonal to interannual time-scale, and suggest that the MJO introduces a stochastic element into the predictions on these time-scales.

The results shown in this paper demonstrate that the unpredictable nature of the MJO does not appear to destroy or disrupt the reproducibility of the seasonal cycle when this is quantified in planetary-scale terms. It is possible that the apparent contradiction between the stochastic behaviour of the MJO and the reproducibility of the seasonal cycle, suggestive of a separation between the inherent predictability of these two time-scales, may also extend to the spatial-scale. There is evidence for the MJO affecting the seasonal cycle on the regional-scale, for example, by influencing the timing of the onset of the Asian and Australian summer monsoons (e.g. Murakami et al. 1986; Hendon and Liebmann 1990). Similarly, several authors have suggested that the seasonal mean regional anomalies, such as those in the All India Rainfall (AIR), are influenced by the intraseasonal activity (e.g. Gadgil and Asha 1992). This scenario suggests that prediction on the seasonal to interannual time-scale may only be possible for the larger space-scales. The analogy can be drawn with the predictability of the Asian summer monsoon, in which GCMs have the
capability to reproduce the interannual behaviour of the large-scale monsoon circulation but are unable to simulate the regional AIR anomalies (e.g. Ju and Slingo 1995; Sperber and Palmer 1996). An understanding of the relationship between time- and space-scales of intraseasonal and interannual variability is essential for progress in seasonal and climate prediction.

So why is the activity of the MJO apparently so insensitive to interannual changes in the boundary forcing? The simulated MJO displays the correct seasonality, suggesting that its activity is controlled in some sense by the mean seasonal evolution of the tropical heating and circulation patterns. The important point here is that the mean amplitude of the seasonal cycle is much larger than any interannual variation in the seasonal cycle (cf. Figs. 2, 14 and 15). The change in the tropical heating distribution between northern winter and summer, for example, is much greater than, say, the change from El Niño to La Niña conditions. The fact that the model is able to reproduce the correct seasonality suggests that the MJO is sensitive to some aspects of the boundary forcing, namely the requirement that the SSTs are symmetric about the equator with the diabatic heating maximized over the equator, as proposed by Salby et al. (1994). This condition occurs preferentially during northern winter and spring and it is important to note that this condition is not affected by El Niño which primarily displaces the heating longitudinally. This fact may be one reason why the activity of the MJO appears to be insensitive to interannual SST anomalies, specifically those associated with El Niño.

The teleconnection patterns from the NCEP/NCAR Reanalysis (Fig. 9) and from the integrations with HadAM2a (Fig. 12) both show that the sporadic occurrence of the MJO is only weakly influenced by SST forcing and that it may therefore involve a stochastic process such as the influence of the extratropics. It is generally accepted that the MJO is initiated over the Indian Ocean (e.g. Wang and Rui 1990). Based on a case study of a strong event in 1985/86, Hsu et al. (1990) proposed that the MJO is initiated by the ‘flaring’ of convection over the Indian Ocean in response to the vertical motion field associated with a subtropical Rossby wave train. The role of the extratropics in influencing the behaviour of the MJO clearly warrants more investigation and may hold the key to explaining the lack of predictability for the activity of the MJO.

It is important to stress the limitations of the modelling part of the present study. Firstly, the results may be model dependent, and although the model produces an MJO with some realistic characteristics, there are known shortcomings (Sperber et al. 1997). Secondly, the model is uncoupled and forced by observed SSTs. This precludes any interaction between the ocean and the atmosphere. There is increasing evidence for a coherent modulation of the SST by the MJO which may be important for the propagation and maintenance of the MJO (e.g. Lau and Sui 1997; Sperber et al. 1997). In addition, the influence of year-to-year variations in the activity of the MJO on the evolution of El Niño is not well understood although it may be substantial. Both factors point to the need for numerical experimentation with coupled atmosphere–ocean models to address these questions.

With regard to the robustness of the results from the NCEP/NCAR Reanalysis, it should be noted again that substantial areas of the tropics are data sparse, and that consequently the analysis may depend heavily on the characteristics of the forecast model used to provide the first guess. Significant differences between the ECMWF Reanalysis and the NCEP/NCAR Reanalysis have been noted in the mean and variability of the Asian summer monsoon for the period 1979–95 (Annamalai et al. 1999). It will be important therefore to compare the behaviour of the MJO in the planned 40-year reanalysis at ECMWF when it becomes available.

During the early months of 1997 the tropical Pacific Ocean underwent a major transition from La Niña conditions in December 1996 to a major El Niño by June 1997 with,
ultimately, peak SST anomalies in the east Pacific in excess of 5 K. This period was characterized by strong MJO activity with very energetic WWBs embedded in the active phase of the MJO (Slingo 1998). A series of downwelling oceanic Kelvin waves were generated by these WWBs with major displacements of the thermocline. These oceanic Kelvin waves propagated across the Pacific, manifesting themselves at the surface in the east Pacific and cumulatively giving rise to substantial increases in the local SST. It is notable that the strong intraseasonal activity in the zonal wind was a particular feature of the winter and spring of 1996/97, not seen in the previous year (Fig. 3).

The development of the 1997 El Niño is a striking example of how intraseasonal activity in the atmosphere, generating intraseasonal activity in the ocean, appears to have a major impact on the interannual behaviour of the coupled atmosphere–ocean system. The growth of the 1997 El Niño was more rapid than any other since 1950, again suggestive of the significant influence of intraseasonal atmospheric forcing on the development of this event, although more research is needed to provide a definitive answer. If the activity of the MJO is stochastic, as the results from the NCEP/NCAR Reanalysis and HadAM2a suggest, then the prospects for predicting such an El Niño event more than a few months in advance are possibly limited.

The question still remains, however, as to whether the coupled atmosphere–ocean system may, in certain circumstances, be predisposed to intraseasonal activity. This may not necessarily be manifested in SST anomalies but in more complex characteristics of the atmosphere and the upper layers of the ocean. MJOs and WWB events tend to form in clusters such that the oceanic response to the first event predisposes the system towards an active second event. Although the ability of atmosphere-only models to simulate MJOs has been well documented through AMIP, a similar study is needed for coupled models and will be a future topic of research.

7. Conclusions

The interannual variability in the activity of the MJO has been investigated using the 40-year NCEP/NCAR Reanalysis for 1958–97, and a 4-member ensemble of 45-year integrations with the Hadley Centre climate model (HadAM2a), forced with observed SSTs for 1949–93. In particular a relationship with SST was sought with the aim of assessing the potential predictability of MJO activity.

The NCEP/NCAR Reanalysis was used to decide on a suitable index to describe the year-to-year variations in MJO activity. The teleconnection patterns between this MJO index and SST showed a weak, non-significant relationship with the suggestion that the MJO is more active in cold (La Niña) phases of El Niño. However, an interdecadal trend in MJO activity was noted in the NCEP/NCAR Reanalysis, which was confirmed by the model results, with the suggestion that it might be related to a long-term increase of tropical SSTs during the period of the study.

The potential lack of predictability for the year-to-year changes in MJO activity suggested by the NCEP/NCAR Reanalysis, has been confirmed by the results from the ensemble of model integrations. The reproducibility between ensemble members was small, and again the teleconnection patterns between the MJO index and SST showed no regions of significant correlation. It can be concluded that the activity of the MJO is not fundamentally controlled by the SST distribution, particularly the phase of El Niño, and would appear to be largely chaotic in character.

The model has successfully captured the observed seasonality in the behaviour of the MJO with greatest activity during northern winter and spring. The possibility that the lack of reproducibility for the interannual behaviour of the MJO may be associated with
a lack of reproducibility for interannual variations in the mean seasonal cycle has been investigated. The results have shown, however, that year-to-year changes in the seasonal cycle are very reproducible.

The implications of these results for the predictability of the tropical atmosphere–ocean system are important since intraseasonal activity in the atmosphere, associated with MJOs and WWBs, can have a substantial impact on the Pacific Ocean. As the events in 1997 indicate, MJO activity may have a significant impact on the magnitude and growth rate of El Niño events. In turn the decadal changes in MJO activity suggest that if tropical SSTs continue to increase, the activity of the MJO also may tend to increase which then might have implications for the future behaviour of El Niño.

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