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On the Predictability of the Interannual Behaviour of the Madden-Julian Oscillation and its Relationship with El Niño

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

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ABSTRACT

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 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 to either 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 timescale 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 uncoupled system, with the atmosphere being driven by imposed SSTs, there is no reproducibility for 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 chaotic in character. However, the model results have confirmed the low frequency, decadal timescale variability of MJO activity seen in the NCEP/NCAR Reanalysis. The activity of the MJO is consistently lower in all realisations prior to the mid 1970s, suggesting that the MJO may become more active as tropical SSTs become warmer. This result may have implications for the effects of global warming on the coupled tropical atmosphere-ocean system.

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

1. Introduction

The intraseasonal or Madden-Julian Oscillation (MJO) is the dominant mode of variability in the tropics at timescales 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 NWP analyses and the basic characteristics of the MJO are now well documented Since the oscillation has such 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 currently 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 has been 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 season 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) Thus, 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 for 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 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 be achieved also in ensemble seasonal prediction is an important question and would depend 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), and 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 25K 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 dateline 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 Westerly Wind Bursts (WWB), 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 timescales 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 NCEP/NCAR 40-year 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 resolution of T62, 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 initialisation. 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 have been used.

As well as the Reanalysis, outgoing longwave radiation (OLR) from the Advanced Very High Resolution Radioameter (AVHRR) on the 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 2.5^0 latitude/longitude grid with missing values filled by interpolation (Liebmann and Smith 1996). This dataset 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 bandpass 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

3.1 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 (upper panel) shows the dominant modes of intraseasonal variability in the observed OLR data for 1979-97 as described by Empirical Orthogonal Function (EOF) analysis. These modes basically describe the convective maxima over the Indian Ocean and West Pacific associated with the active phase of the MJO. The timeseries of the first two principal components (PC1 and PC2, Figure 1 lower panel) 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 timeseries of the two dominant PCs (Figure 1). 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

87, 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 PCs in Figure 1 shows that the largest modulation of the OLR at intraseasonal timescales is associated with MJO events rather than other types of intraseasonal variability Therefore it is essential to identify 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 timeseries of the type shown in Figure 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 timescales 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 Figure 2 where the evolution of [u] at 200hPa, averaged between 10^0N and 10^0S, 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 (Both are 100 point Lanczos filters as used in Slingo et al (1996)) 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 Figure 2 are similar to the diagnosis of the earlier ECMWF Analyses by the Joint Diagnostics Project (JDP, Hoskins et al 1989) and shown in Figure 11 of Slingo et al (1996)

As the lower panel of Figure 2 shows, the intraseasonal variations in [u] are of the order of ± $2ms^{-1}$, 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 Figure 3, the variance of the bandpass (20-100 days) filtered [u] from Figure 2 (lower panel) has been computed and then plotted within a 100-day moving window As in Figure 14 from Slingo et al (1996), this essentially shows how the intraseasonal activity is modulated at lower frequencies associated with seasonal and interannual timescales Also shown in Figure 3 are the SST anomalies for the Niño3 (5^0N-5^0S, 90^0W-150^0W) region of the central and East

Pacific Again the similarity between the results from the NCEP/NCAR Reanalysis (Figure 3 of this paper) and from the operational ECMWF Analyses (Figure 14 of Slingo et al 1996) is reassuring

Comparison of Figure 3 with the PC timeseries shown in Figure 1, suggests that the variance of the bandpass 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 Figure 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 from such a limited sample and may well require an extended reanalysis dataset 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 diagnosed

The dominant modes of intraseasonal variability in the 20-100 day bandpass filtered velocity potential (χ) and eddy streamfunction (ψ^*) at 200hPa from the NCEP/NCAR Reanalysis for 1958-97 are shown in Figure 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 (Figure 1), EOF1 and EOF2 are reversed The eddy streamfunction 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 streamfunction are highly correlated (>0 9) at zero lag, confirming the coupled Kelvin-Rossby wave structure found in other studies based on shorter period datasets (e g Rui and Wang 1990) As with the OLR observations (Figure 1), the PC timeseries show eastward propagation in which PC2 leads PC1 by approximately 10 days for both velocity potential and eddy streamfunction The lag correlation coefficients between PC1 and PC2 are 0 72 and 0 65 for velocity potential and eddy streamfunction, respectively

As noted earlier, the MJO influences the zonal mean of the zonal wind, [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 streamfunction 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 bandpass filtered zonal streamfunction ([ψ]) 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 ($[u]_\psi = -d[\psi]/dy$) 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 $[u]_\psi$ show that PC1 leads PC2 by 10-15 days with a lag correlation of ~0.4. PC1 of $[u]_\psi$ has its maximum correlation (0.36) with PC2 of χ 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 $[u]_\psi$ 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 bandpass filtered [u] which was used by Slingo et al. (1996) to describe the seasonal and interannual variations in MJO activity (Figure 3), the correlation between the band pass filtered [u] and the first PC of $[u]_\psi$ is very high (0.86) at zero lag, confirming that the bandpass 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 850hPa zonal wind. This is equivalent to using the PC timeseries of the dominant modes from EOF analysis to describe the activity of the MJO. In Figure 6, various measures of MJO activity are compared, based on the variance of PC1 for χ, ψ^* and $[\psi]$ within a 100-day moving window, for the period 1979-97, coincident with that used in Figures 1-3. As expected the index based on PC1($[u]_\psi$) is very close to that based on bandpass filtered [u] (Figure 3), whereas those based on more regional characteristics (PC1(χ) and PC1(ψ^*)) 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 more successfully than the other more regionally PC-based indices. As an index of MJO activity it is also appealing because it 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 bandpass 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.

3.2. Decadal changes in MJO activity

Taking the MJO index based on the bandpass 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 dataset should be of sufficient length to give a fairly robust signal However, when the MJO index was computed for the full record (Figure 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 90s 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 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 This hypothesis is supported by the temporal characteristics of the dominant modes of χ and ψ^* (Note that the dominant modes were almost identical in structure when the EOF analysis was performed on either the full (1958-97), or the latter portion (1979-97) of the record) 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 region is likely to be very sensitive to the introduction of satellite winds Thus, although the Reanalysis are based on a consistent data assimilation, analysis and forecast system, and also include additional data (e g satellite measurements, field experiments) which were not available operationally, they cannot overcome the overall lack of observations in some regions of the globe

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 timescale variability which can be described by the dominant EOF (explaining 28%of the variance) of the seasonally detrended monthly SSTs, 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, Figure 8, upper panel) During the latter part of 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, Figure 8, lower panel) This sudden, interdecadal change around 1977 in the characteristics of the atmospheric circulation and SST, particularly related to ENSO, has been widely documented (e g Wang 1995, Zhang et al 1997) and is evident also in Figure 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 may provide a possible explanation for the decadal timescale variations in MJO activity However, results from an ensemble of integrations with the Hadley Centre climate model, described in Section 5, support the idea that decadal variations in SST may be influential

3.3. Interannual variability in MJO activity and its teleconnections with SST.

If the decadal variability described in Figure 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 instantanous correlation patterns with the global SSTs averaged for the same months have been produced (Figure 9) The upper panel in Figure 9 shows the teleconnection pattern for the whole record (1958-97) 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 Nino-type relationship with more MJO activity during cold phases, but in neither case are the correlations significant Only in the central 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 χ, as discussed in Section 3 1) Fink and Speth (1998) 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 timescales For the eastern Indian Ocean and the West Pacific, Fink and Speth (1998) found no evidence that interannual variations in SST systematically modify the seasonal MJO activity

In summary, the study of the MJO in the NCEP/NCAR 40 year 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 timescales, 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 which have been forced with obseived 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 UKMO Unified Model It's resolution is 2 5^0 latitude by 3 75^0 longitude with 19 levels in the vertical It was developed from HadAM1, the UKMO's first model submitted to AMIP (described by Phillips 1994), through improvements to the cloud and pıecipitation 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-wateı and ice content, and convective cloud amount), a penetrative convection scheme with stability dependent closure, which represents both updrafts and downdrafts, boundary layer mixing in up to five of the lowest model layers, a land suıface scheme which includes a vegetation canopy model, a four-layer soil model for heat conduction, and a single-layer soil model for moistuıe storage including surface and sub-surface runoff The model's chemistry involves seasonally and meridionally varying ozone profiles, and a fixed caıbon dioxide concentration (321ppmv)

In their analysis of the performance of 15 atmospheric 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 obseıved Similar results have been obtained in a diagnosis of the MJO simulated by HadAM2b in an extended perpetual March integıation (Matthews et al 1998) 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 heıe

Four integrations have been caıried out whilst applying a veısion of the Hadley Centıe Global sea-Ice and Sea Surface Temperature (GISST1 1) data set as a boundary forcing for the period Octobeı 1948 - December 1993 The integrations diffeıed only in theiı initial conditions For the purpose of this study a four member ensemble of integrations was available for the 45 year period, January 1949 - 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 MOHSST5 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 utilised from 1982, and sea-ice extents were taken from NOAA since 1973, prior to that a variety of sources, often climatologies, were used Although the nominal resolution of GISST1 1 is about 5^0, the data are available on a 1^0 grid, which 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.

5.1 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 200hPa, averaged between 10^0N and 10^0S, for the years 1979-93 from one realisation with HADAM2a These 15 years are shown to facilitate comparison with the results from the NCEP/NCAR Reanalysis (Figure 2) As in Figure 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 Figure 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 ms^{-1}) than in the NCEP/NCAR Reanalysis (3 22 ms^{-1}) and the model has failed to capture 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 3

In Figure 10, strong intraseasonal variations in [u] are clearly evident Their amplitude is close to that seen in the NCEP/NCAR Reanalysis (Figure 2) The mean amplitude for all realisations is 1 10 ms^{-1} compared with 1 19 ms^{-1} in the Reanalysis (Note that Slingo et al (1996) reported 1 23 ms^{-1} for the ECMWF analyses for a 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 ms^{-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 (Figures 3 and 7), the behaviour of the 4 realisations is summarised in Figure 11 This index of MJO activity shows that all the realisations contain a few years where the oscillation is particularly active, but that there is no agreement between the realisations for the years involved The reproducibility of the the MJO index for the four realisations has been measured using the 'Analysis of Variance' method, (ANOVA, Rowell et al 1995, Rowell 1997) The calculation essentially estimates the percentage of the variance which is the same in the four timeseries 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 Figure 11, the teleconnection patterns between the seasonal mean MJO index for January to April and the SST distributions have been computed (Figure 12) as for the NCEP/NCAR Reanalysis (Figure 9) The upper panel of Figure 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 (Figure 9), the model results again suggest a marginally significant correlation with warmer 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 (1998), 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

5.2 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 (Figure 7) which might be related to interdecadal changes in tropical SSTs (Figure 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 (Figure 13)

The behaviour of the simulated MJO in Figure 11 suggests that the model has reproduced the change in MJO activity seen in the NCEP/NCAR Reanalysis, with the 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 Figures 7 and 11) for all months has been computed for the years prior to and following 1977 For comparison with the NCEP/NCAR Reanalysis, the values given in brackets are for 1959 onwards The results for each realisation 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 realisations and in the NCEP/NCAR Reanalysis This suggests that, as the tropical SSTs become warmer (see Figures 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 known to be triggered and where it has its greatest convective signal

Table 1 Mean MJO index for all months, for the years shown

Realisation	1	2	3	4	NCEP
1950(59)-92	1 80 (1 85)	1 95 (1 98)	1 91 (2 02)	1 80 (1 75)	(2 30)
1950(59)-76	1 68 (1 73)	1 81 (1 79)	1 65 (1 74)	1 67 (1 51)	(2 05)
1977-92	2 00	2 19	2 34	2 02	2 60

It would be tempting to draw conclusions from the reproducibility of decadal timescale changes in MJO activity, and its relationship with tropical SSTs, in terms of the consequences of global warming for the behaviour of the MJO The fact that there does not appear to be a relationship between SST and MJO activity at interannual timescales suggests that the mechanism behind such a relationship is far from clear and that a more extensive and careful study is required before any such statements could be made

5.3 Relationship between interannual changes in MJO activity and in the seasonal cycle

The observed MJO displays a marked seasonality in its occurence, being most prevalent in northern winter and spring Using the MJO indices shown in Figures 7 and 11, the seasonal cycle of MJO activity has been computed for the NCEP/NCAR Reanalysis and for each realisation with HadAM2a The results confirm that the observed MJO is most active in the early months of the year with peak activity occuring 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 timescales 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 timescale, 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 (Figure 2) and in the model results (Figure 10) The reproducibility of the seasonal cycle in the four realisations 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 realisation (Figure 14) The deviation of the low pass filtered [u] from the mean seasonal cycle shows considerable interannual variability in the seasonal cycle which 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 realisations has been quantified using the ANOVA method The results show that 63% of the variations in the seasonal cycle are the same in each realisation 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 timescale 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 timeseries (Figure 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 years' integration time is seen which also appears to be highly reproducible Also included in Figure 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

These results shown in Figure 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 [u]) 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, beyond the scope of this paper Nevertheless the model results have demonstrated a clear relationship between the seasonal cycle and SST which is not seen in the activity of the MJO

6. Implications of the results and their relevance to the development of the 1997/98 El Niño.

Although the central theme of the 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 timescales 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), but yet the activity of the MJO is insensitive to both 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 timescale 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 timescale They preclude, therefore, the potential for predictability of the activity of the MJO on the seasonal to interannual timescale and suggest that the MJO introduces a stochastic element into the predictions on these timescales

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 timescales, 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 timescale 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 (c f Figures 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 maximised 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 only 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 (Figure 9) and from the integrations with HadAM2a (Figure 12) both show that the sporadic occurence 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 sub-tropical 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 ocean-atmosphere 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 (ERA) and the NCEP/NCAR Reanalysis have been noted in the mean and variability of the Asian Summer Monsoon (Annamalai et al 1998) for the period 1979-95 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 peak SST anomalies in the East Pacific in excess of 3K This period was characterised 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

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 ocean-atmosphere 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. An interdecadal trend in MJO activity was noted, which was confirmed by the model results and therefore might be related to a long-term warming 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 seasonal cycle has been investigated The results have shown that year to year changes in the seasonal cycle are very reproducible

The implications of these results for the predictability of the tropical ocean-atmosphere 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

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References

Annamalai, H , J M Slingo, K R Sperber and K Hodges, 1998 The mean evolution and vaiiability of the Asian Summer Monsoon Comparison of ECMWF and NCEP/NCAR Reanalyses Submitted to *Mon Weath Rev*

Aıkin, P A and P E Ardanuy, 1989 Estimating climatic-scale precipitation from space A review *J Clim* , **2**, 1229-1238

Bladé, I and D L Hartmann, 1993 Tropical intraseasonal oscillations in a simple nonlinear model *J Atmos Sci* , **50**, 2922-2939

Bottomley, M , Folland, C K , Hsiung, J , Newell, R E and Parker, D E , 1990 Global Ocean Surface Temperature Atlas Joint Met Office/MIT Project, 20pp + 313 plates, funded by UK Depts of Energy and Environment, HMSO, London

Ferranti, L , T N Palmer, F Molteni and E Klinker, 1990 Tropical-extratropical interaction associated with the 30-60 day oscillation and its impact on medium and extended range prediction *J Atmos Sci* , **47**, 2177-2199

Fink, A and P Speth, 1998 Some potential forcing mechanisms of the year-to-year variability of the tropical convection and its intraseasonal (25-70 day) variability *Int J of Climatol* , in press

Gadgil, S and G Asha, 1992 Intraseasonal variation of the summer monsoon I Observational aspects *J Meteorol Soc Japan*, **70**, 517-527

Gu, D and S G H Philandeı, 1995 Seculaı changes of annual and interannual vaıiability in the tıopics during the past century *J Clim* , **8**, 864-876

Hendon, H H and J Glick, 1997 Intıaseasonal aiı-sea interaction in the tıopical Indian and Pacific Oceans *J Clim* , **10**, 647-661

Hendon, H H and B Liebmann, 1990 The intıaseasonal (30-50 day) oscillation of the Australian summer monsoon *J Atmos Sci* , **47**, 2909-2923

Hendon, H H , B Liebmann and J D Glick, 1998 Oceanic Kelvin waves and the Madden-Julian Oscillation *J Atmos Sci* , **55**, 88-101

Hoskins, B J , H H Hsu, I N James, M Masutani, P D Sardeshmukh and G H White, 1989 Diagnostics of the global atmospheıic circulation based on ECMWF analyses 1979-1989 WCRP-27, World Meteorological Organization, Geneva

Hsu, H , B J Hoskins and F Jin, 1990 The 1985/86 intraseasonal oscillation and the role of the extıatıopics *J Atmos Sci* , **47**, 823-839

Ju, J and J M Slingo, 1995 The Asian Summer Monsoon and ENSO *Q J R Meteorol Soc* , **121**, 1133-1168

Kalnay, E , M Kanamitsu, R Kistler, W Collins, D Deaven, L. Gandin, M Iredell, S Saha, G White, J Woollen, Y Zhu, M Chelliah, W Ebisuzaki, W Higgins, J Janowiak, K C Mo, C Ropelewski, J Wang, A Leetma, R Reynolds, R Jenne and D Joseph, 1996 The NCEP/ NCAR 40-year reanalysis project *Bull Amer Met Soc* , **77**, 437-471

Kessler, W S and M J McPhaden, 1995 Oceanic equatorial Kelvin waves and the 1991-1993 El Niño *J Clim* , **8**, 1757-1774

Kessler, W S , M J McPhaden and K M Weickmann, 1995 Forcing of intraseasonal Kelvin waves in the equatorial Pacific *J Geophys Res* , **100**, 10613-10631

Kiladis, G N , G A Meehl and K M Weickmann, 1994 The large scale circulation associated with westerly wind bursts and deep convection over the western equatorial Pacific *J Geophys Res* , **99**, 18527-18544

Kindle, J C and P A Phoebus, 1995 The ocean response to operational westerly wind bursts *J Geophys Res* , **100**, 4893-4920

Kousky, V E and M T Kayano, 1994 Principal modes of Outgoing Longwave Radiation and 250mb circulation for the South American sector *J Clim* , **7**, 1131-1143

Lau, W K-M and P H Chan, 1988 Interannual and intraseasonal variations of tropical convection A possible link between the 40-50 day oscillation and ENSO? *J Atmos Sci* , **44**, 506-521

Lau, W K-M and C H Sui, 1997 Mechanisms of short-term sea surface temperature regulation Observations during TOGA-COARE *J Clim* , **10**, 465-472

Lau, K M , I M Held and J D Neelin, 1988 The Madden-Julian oscillation in an idealized general circulation model *J Atmos Sci* , **45**, 3810-3832

Liebmann, B and C A Smith, 1996 Description of a complete (interpolated) OLR dataset *Bull Amer Met Soc* , **77**, 1275-1277

Lim, H , C -P Chang and T -K Lim, 1991 Vertical wind shear effects on Kelvin wave-CISK modes Possible relevance to 30-60 day oscillations *Terrestrial, Atmospheric and Oceanic Sciences*, **2**, 203-216

Madden, R A , and P R Julian, 1994 Observations of the 40 - 60 Day Tropical Oscillation - A Review *Mon Weath Rev* , **122**, 814-835

Magaña, V , 1993 The 40- and 50-day oscillations in atmospheric angular momentum at various latitudes, *J Geophys Res* , 98 10,441-10,450

Matthews, A J , 1993 The Intraseasonal Oscillation PhD Thesis, Department of Meteorology, University of Reading, Reading, UK

Matthews, A J , J M Slingo, B J Hoskins and P M Inness, 1998 Fast and slow kelvin waves in the Madden-Julian Oscillation of a GCM Submitted to *Q J R Meteorol Soc*

Murakami, T , L-X Chen and A Xie, 1986 Relationship among seasonal cycles, low-frequency oscillations, and transient disturbances as revealed from Outgoing Longwave Radiation data *Mon Weath Rev*, **114**, 1456-1465

Nakazawa, T , 1988 Tropical supei clusters within intraseasonal vaiiations over the western Pacific *J Meteor Soc Japan*, **66**, 823-839

Palmer, T N , 1994 Chaos and predictability in foiecasting the monsoon *Proc Indian nat Sci Acad*, **60**, No 1, 57-66

Paikei, D E , Folland, C K , Bevan, A , Ward, M N , Jackson, M , and Maskell, K 1995 Marine surface data for analyses of climatic fluctuations on interannual to century time scales In "Natural Climate Vaiiability on Decade to Century Time scales", Martinson, D G , Bryan, K , Ghil, M , Hall, M M , Kaıl, T R , Sarachik, E S , Sorooshian, S and Talley, L D , Eds , National Academy Press, Washington, 241- 250

Philander, S G H , 1990 El Niño, La Niña, and the Southein Oscillation Academic Piess, 242pp

Phillips, T J , 1994 A summary documentation of the AMIP models PCMDI Report No 18, Univ of Calif , Lawrence Livermoie National Laboratory, Calif

Rowell, D P , 1997 Assessing potential seasonal predictability with an ensemble of multi-decadal GCM simulations *J Clim* , in piess

Rowell, D P , C K Folland, K Maskell, and M N Ward, 1995 Vaiiability of Summer rainfall over Tropical North Afiica (1902-92) Obseivations and Modelling *Q J R Meteorol Soc* , **121**, 699-704

Rui, H and B Wang, 1990 Development characteristics and dynamic structure of tiopical intraseasonal convection anomalies, *J Atmos Sci* , **47**, 357-379

Salby, M L and H H Hendon, 1994 Intraseasonal behavior of clouds, temperature and motion in the tropics *J Atmos Sci* , **51**, 2207-2224

Salby, M L , R R Garcia and H H Hendon, 1994 Planetary-scale circulations in the presence of climatological and wave-induced heating *J Atmos Sci* , **51**, 2344-2367

Slingo, J M , 1998 The 1997/98 El Niño *Weather* (in press)

Slingo, J M and R A Madden, 1991 Characteiistics of the tropical intraseasonal oscillation in the NCAR community climate model *Q J R Meteorol Soc* , **117**, 1129-1169

Slingo, J M , K R Sperber, J S Boyle, J -P Ceron, M Dix, B Dugas, W Ebisuzaki, J Fyfe, D Gregory, J -F Gueremy, J Hack, A Harzallah, P Inness, A Kitoh, W K -M Lau, B McAvaney, R Madden, A Matthews, T N Palmer, C -K Paık, D Randall, N Renno, 1996 Intraseasonal oscillations in 15 Atmospheiic General Ciiculation Models Results from an AMIP diagnostics subproject *Climate Dynamics*, **12**, 325-357

Sperber, K R and T N Palmer, 1996 Interannual tropical rainfall variability in general circulation model simulations associated with the Atmospheric Model Intercomparison Project *J Clim* , **9**, 2727-2750

Sperber, K R , J M Slingo, P M Inness and W K-M Lau, 1997 On the maintenance and initiation of the intraseasonal oscillation in the NCEP/NCAR Reanalysis and the GLA and UKMO AMIP simulations *Climate Dynamics*, **13**, 769-795

Wang, B , 1995· Interdecadal changes in El Niño onset in the last four decades *J Clim* , **8**, 267-285

Wang, B and H Rui, 1990 Synoptic climatology of transient tropical intraseasonal convection anomalies 1979-1985 *Meteorol Atmos Phys* , **44**, 43-61

Weickmann, K M , S J S Khalsa and J Eischeid, 1992 The atmospheric angular momentum cycle during the Madden-Julian oscillation *Mon Weath Rev* , **120**, 2252-2263

Zhang, C , 1997 Intraseasonal varaibility of the upper-ocean thermal structure observed at 0 and 165E *J Clim* , **10**, 3077-3092

Zhang, C and H H Hendon, 1997 Propagating and standing components of the intraseasonal oscillation of tropical moist convection *J Atmos Sci* , **54**, 741-752

Zhang, Y , J M Wallace and D S Battisti, 1997 ENSO-like interdecadal variability 1900-93 *J Clim* , **10**, 1004-1020

Figures

Figure 1 (a) Dominant modes of the intraseasonal vaiiability in the daily Outgoing Longwave Radiation (OLR) measuied by the AVHRR for 1979-97 EOF1 and EOF2 explain 13% and 8% of the variance, respectively Negative contouis (i e enhanced convection) are solid, positive contours are dashed (b) Example of the time series of the principal components, PC1 (solid) and PC2 (dashed), of the dominant modes

Figure 2 Time seiies of the upper tropospheric zonal mean of the zonal wind ([u], ms^{-1}) averaged between 10^0N and 10^0S from NCEP/NCAR Reanalysis for 1979-97 total (uppei panel, thin line), low pass filtered (> 100 days, upper panel, thick line) and band pass filtered (20-100 days, lower panel)

Figure 3 Inteiannual vaiiability in the activity of the MJO as depicted by the time series of the variance (m^2s^{-2}) of the band pass filtered [u] as shown in Figure 2 (lower panel) from the NCEP/NCAR Reanalysis for 1979-97 A 100-day running mean has been applied to the vaiiance time series The lower, shaded curve is the sea surface temperature anomaly (K) for the Niño3 region

Figure 4 Dominant modes (EOF1 and EOF2) of the intiaseasonal vaiiability in the 200hPa velocity potential (χ) and eddy streamfunction (ψ^*) from the NCEP/NCAR Reanalysis for 1958-97

Figure 5 Dominant modes (EOF1 and EOF2) of the intraseasonal variability in the 200hPa zonal streamfunction ([ψ]) from the NCEP/NCAR Reanalysis for 1958-97, expressed in terms of the rotational part of the zonal mean of the zonal flow($[u]_\psi$)

Figure 6 Compaiison of measures of MJO activity based on the variance of (a) PC1 of 200hPa velocity potential (χ), (b) PC1 of 200hPa eddy streamfunction (ψ^*), and (c) variance of PC1 of 200hPa zonal streamfunction ([ψ]) from NCEP/NCAR Reanalysis A 100-day running mean has been applied to the vaiiance time series The lower, shaded curve in all panels is the sea suiface tempeiature anomaly (K) for the Niño3 region

Figure 7 Index of MJO activity based on the variance of the bandpass filtered [u] (see Figure 3) for the complete record, 1958-97 from NCEP/NCAR Reanalysis The lower, shaded curve is the sea surface temperature anomaly (K) for the Niño3 iegion

Figure 8 Fiist EOF of the seasonally detiended monthly mean SSTs as used in the NCEP/NCAR Reanalysis for 1958-97 for the domain 20°N-20°S, 60°E-180°E (upper panel) Positive contours are solid and negative contouis are dashed Timeseiies of the first principal component (PC1, lowei panel)

Figure 9 Teleconnection patterns of the seasonal mean (January-April) MJO index with SST for the whole period (1958-97, upper panel) and foi the lattei pait of the iecord (1977-97, lowei panel) from NCEP/NCAR Reanalysis Correlations with an absolute value greater than 0 3 are significant at the 95% level for the upper panel (0 6 for the lower panel) The contour interval is 0 1 with positive contouis solid, negative contours dashed, and negative values less than -0 1 shaded

Figure 10 As Figure 2 but fiom a single iealisation with HADAM2a foi the last 15 years of integiation

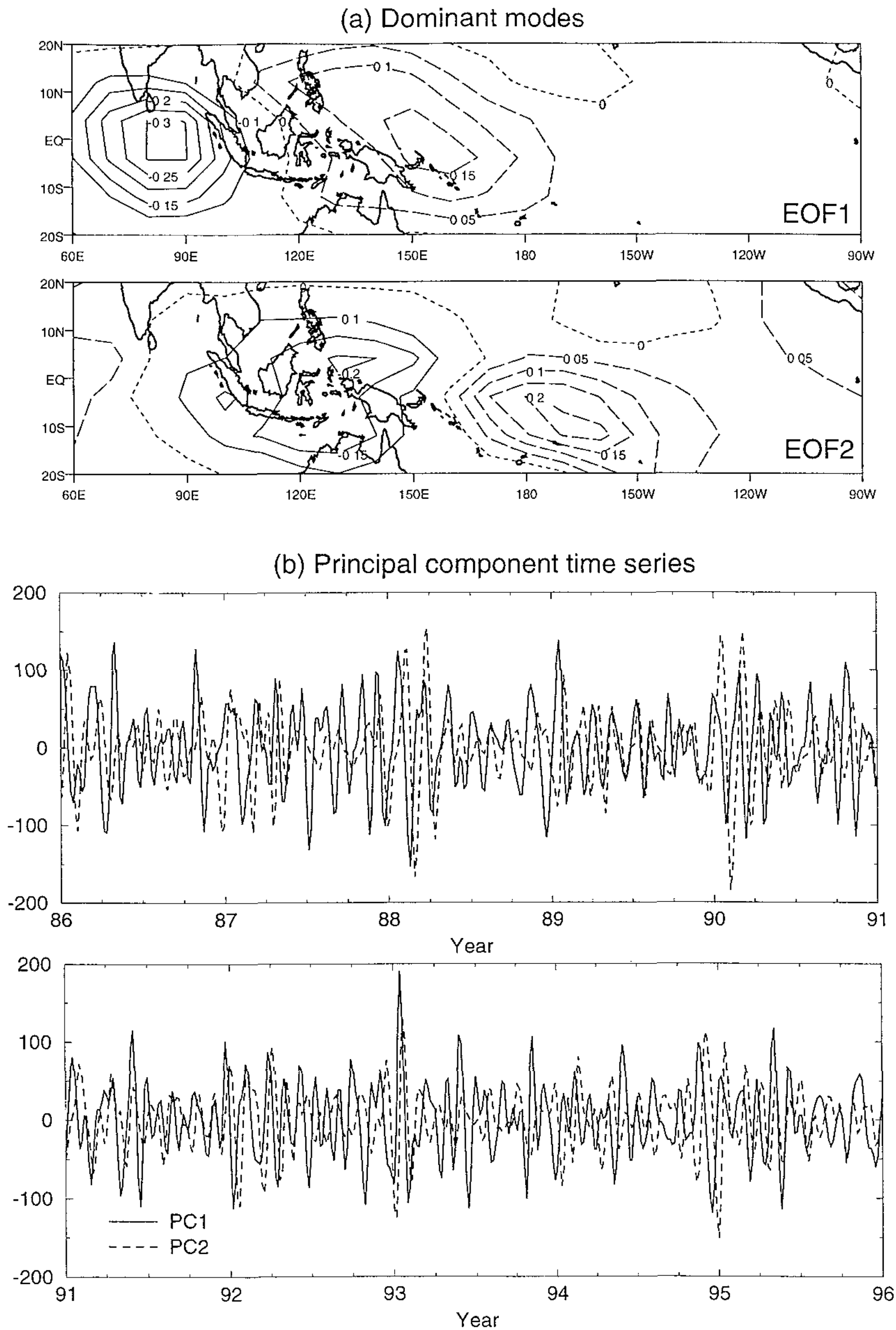
Figure 11 Interannual variability in the activity of the MJO as simulated by each member of the ensemble of model integrations As in Figure 7, the variance of the bandpass filtered [u] is used with a 100-day running mean applied

Figure 12 Teleconnection patterns of the seasonal mean (January-April) MJO index with SST 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

Figure 13 Timeseries of the principal component (PC1) of the first EOF of the seasonally detrended monthly mean SSTs for 1949-93 from GISST1 1 for the domain 20°N-20°S, 60°E-180°E

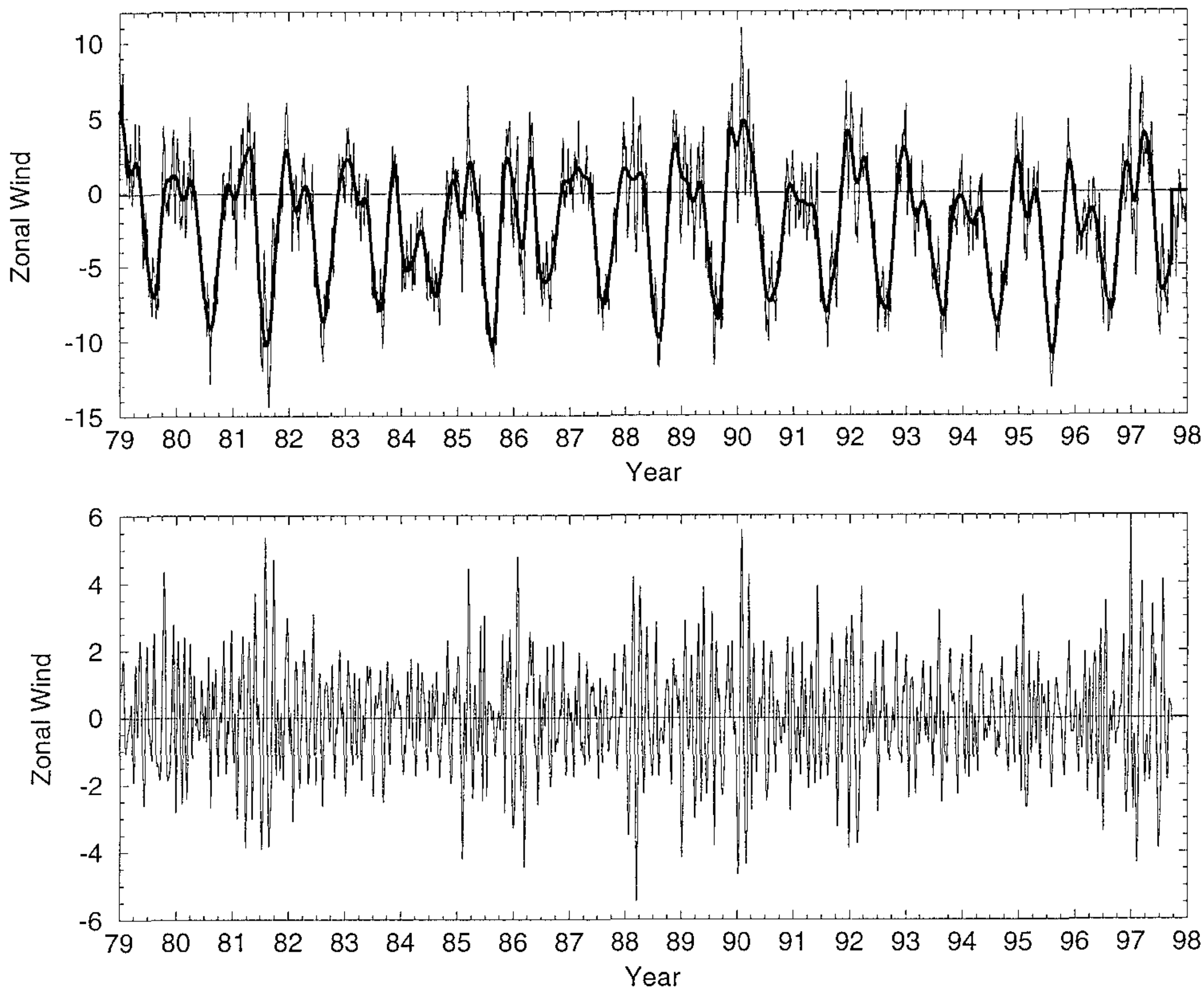
Figure 14· Example of the time series of the deviation of the low pass (> 100 days) [u] from its mean seasonal cycle using results from NCEP/NCAR Reanalysis (solid) and from a realisation with HADAM2a (dashed)

Figure 15 Time series of the deviation of the low pass (> 100 days) [u] from its mean seasonal cycle after application of a 360-day running mean to isolate the low frequency, interannual behaviour of the seasonal cycle in [u] The results from each ensemble member (thin), the ensemble mean (thick solid) and from the NCEP/NCAR Reanalysis (thick dashed) are shown



(a) Dominant modes
EOF1
EOF2
20N
10N
EQ
10S
20S
60E
90E
120E
150E
180
150W
120W
90W
(b) Principal component time series
PC1
PC2
Year

Figure 1



10
5
0
-5
-10
-15
Zonal Wind
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
Year
6
4
2
0
-2
-4
-6
Zonal Wind
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
Year

Figure 2

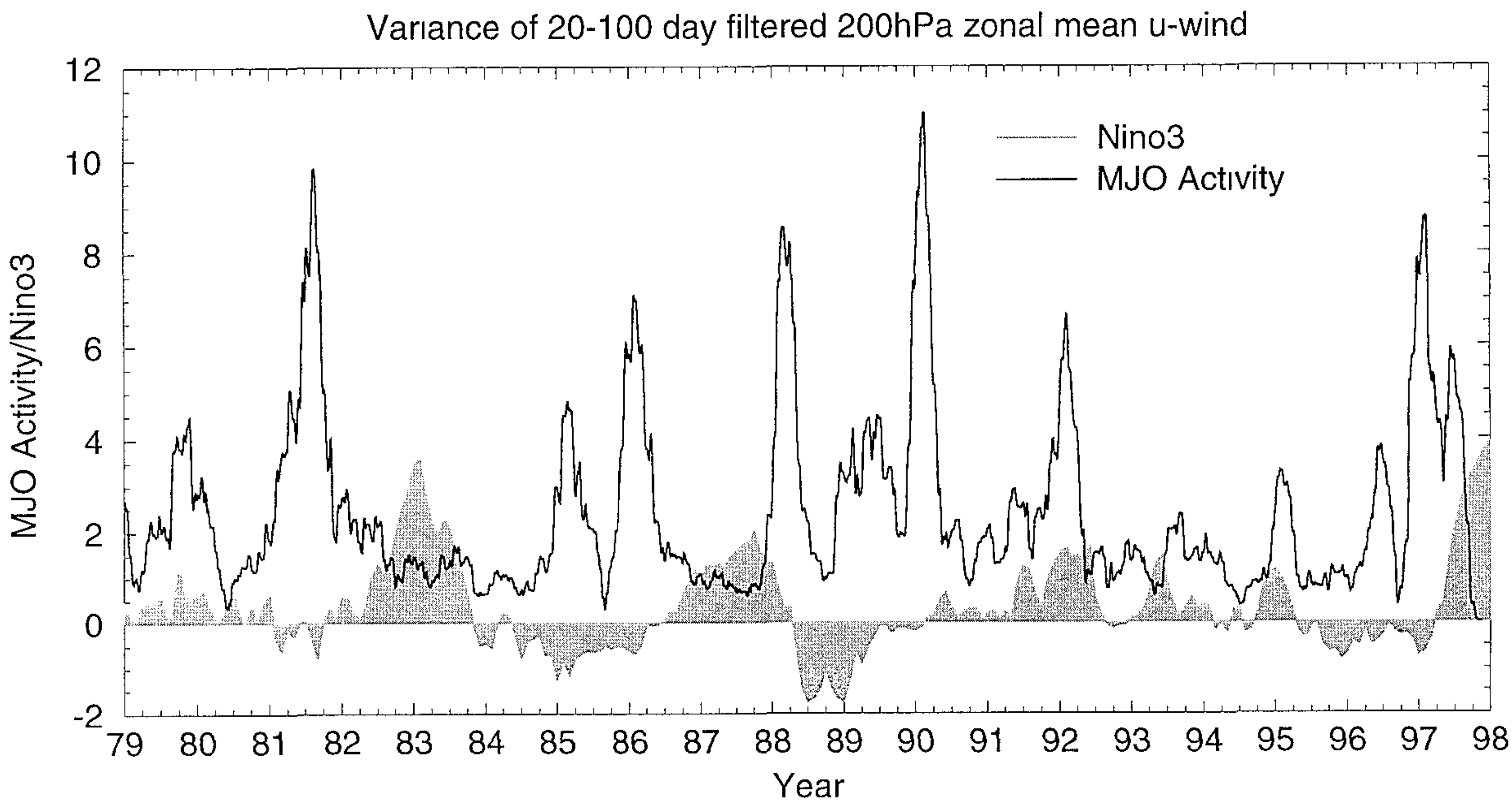

Variance of 20-100 day filtered 200hPa zonal mean u-wind
Nino3
MJO Activity
MJO Activity/Nino3
12
10
8
6
4
2
0
-2
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
Year

Figure 3

Dominant modes of 200hPa velocity potential (χ) and eddy streamfunction (ψ^*)

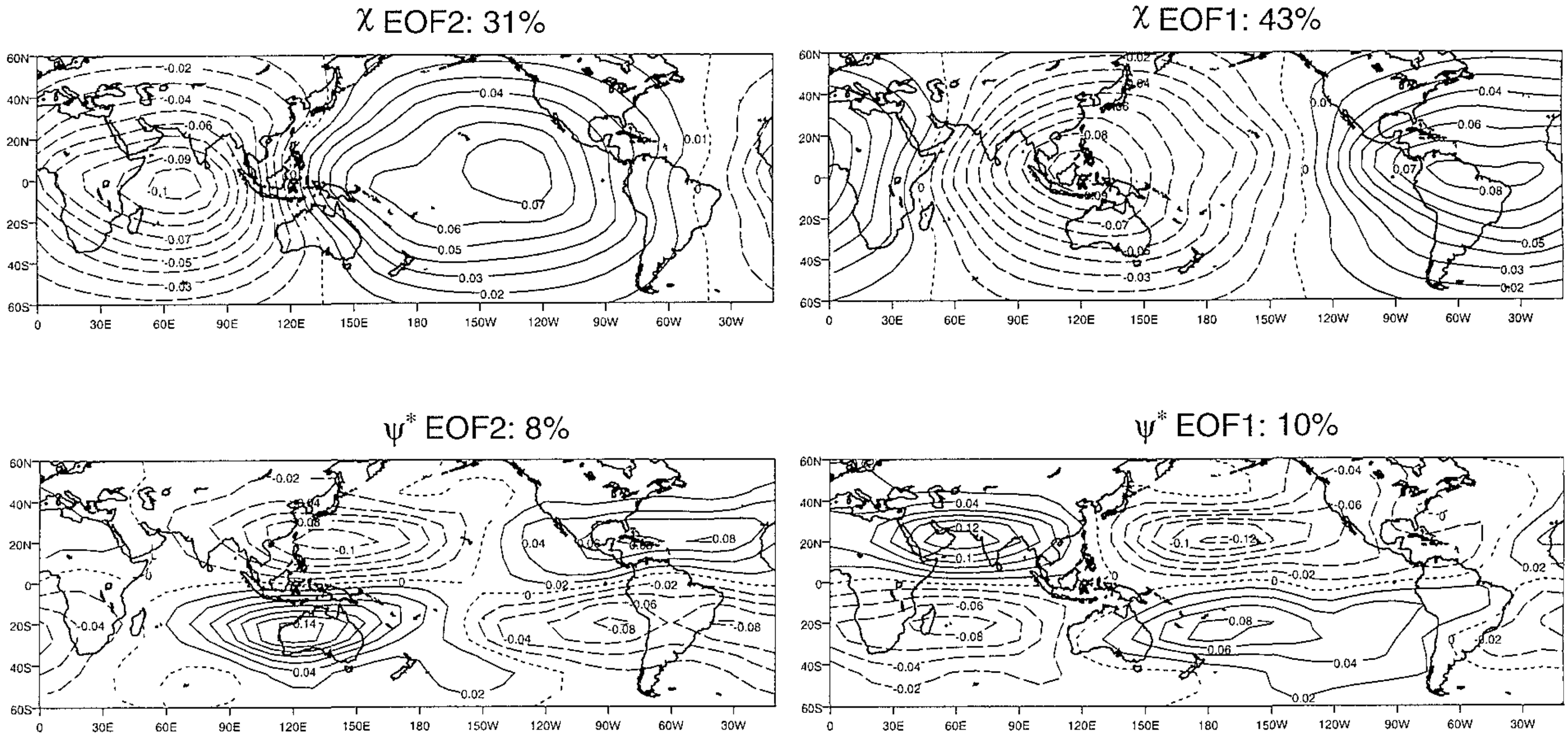
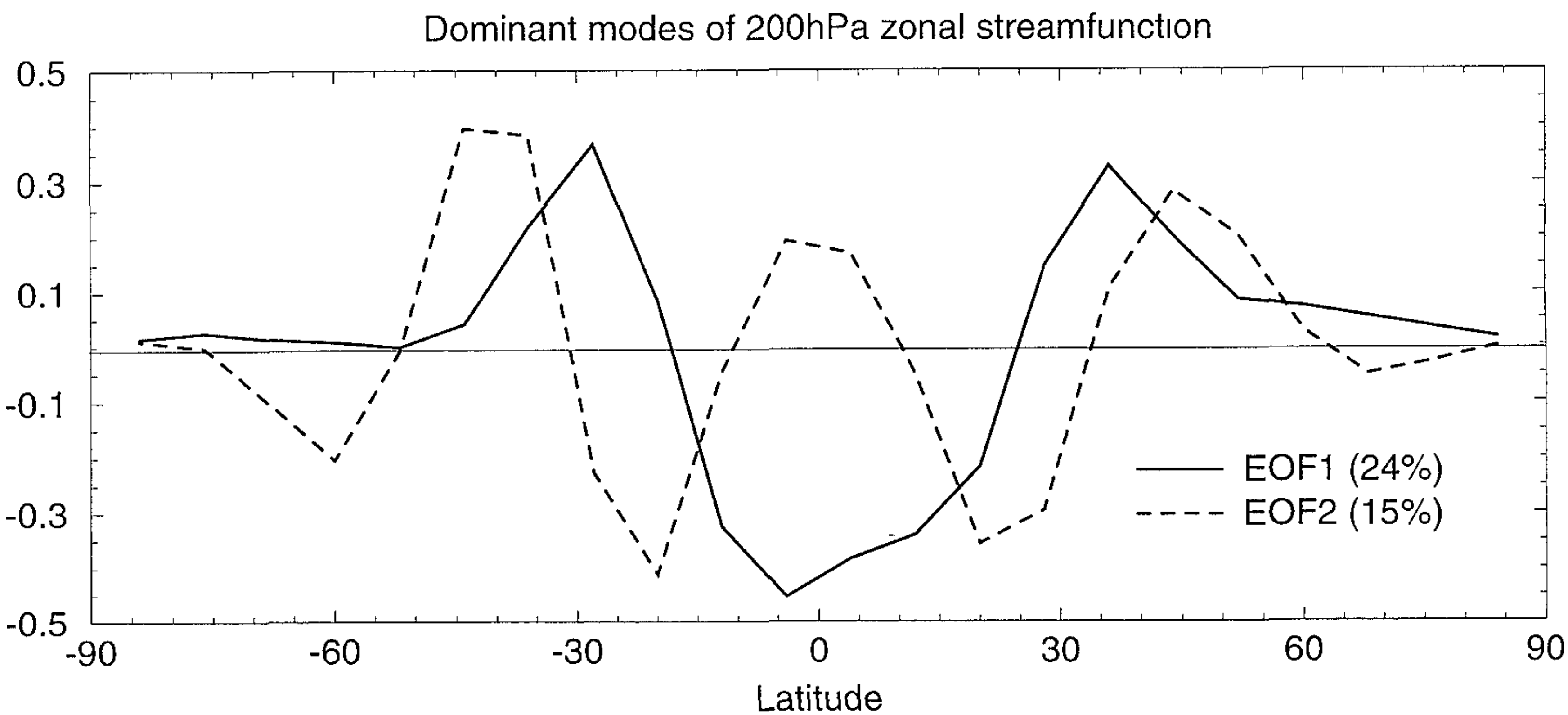


Figure 4



Dominant modes of 200hPa zonal streamfunction
0.5
0.3
0.1
-0.1
-0.3
-0.5
-90
-60
-30
0
30
60
90
Latitude
EOF1 (24%)
EOF2 (15%)

Figure 5

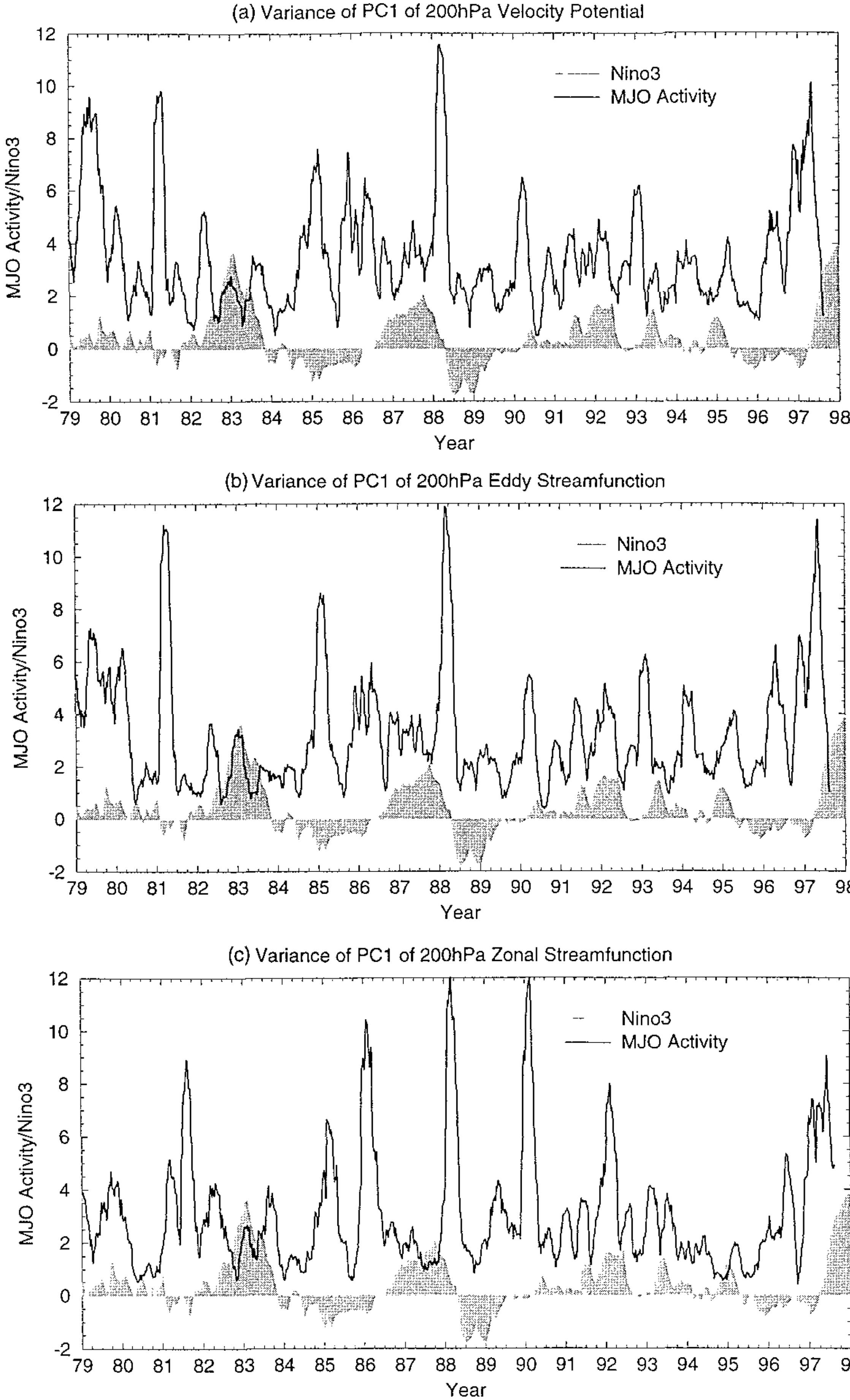

(a) Variance of PC1 of 200hPa Velocity Potential
Nino3
MJO Activity
MJO Activity/Nino3
Year
(b) Variance of PC1 of 200hPa Eddy Streamfunction
Nino3
MJO Activity
MJO Activity/Nino3
Year
(c) Variance of PC1 of 200hPa Zonal Streamfunction
Nino3
MJO Activity
MJO Activity/Nino3
Year

Figure 6

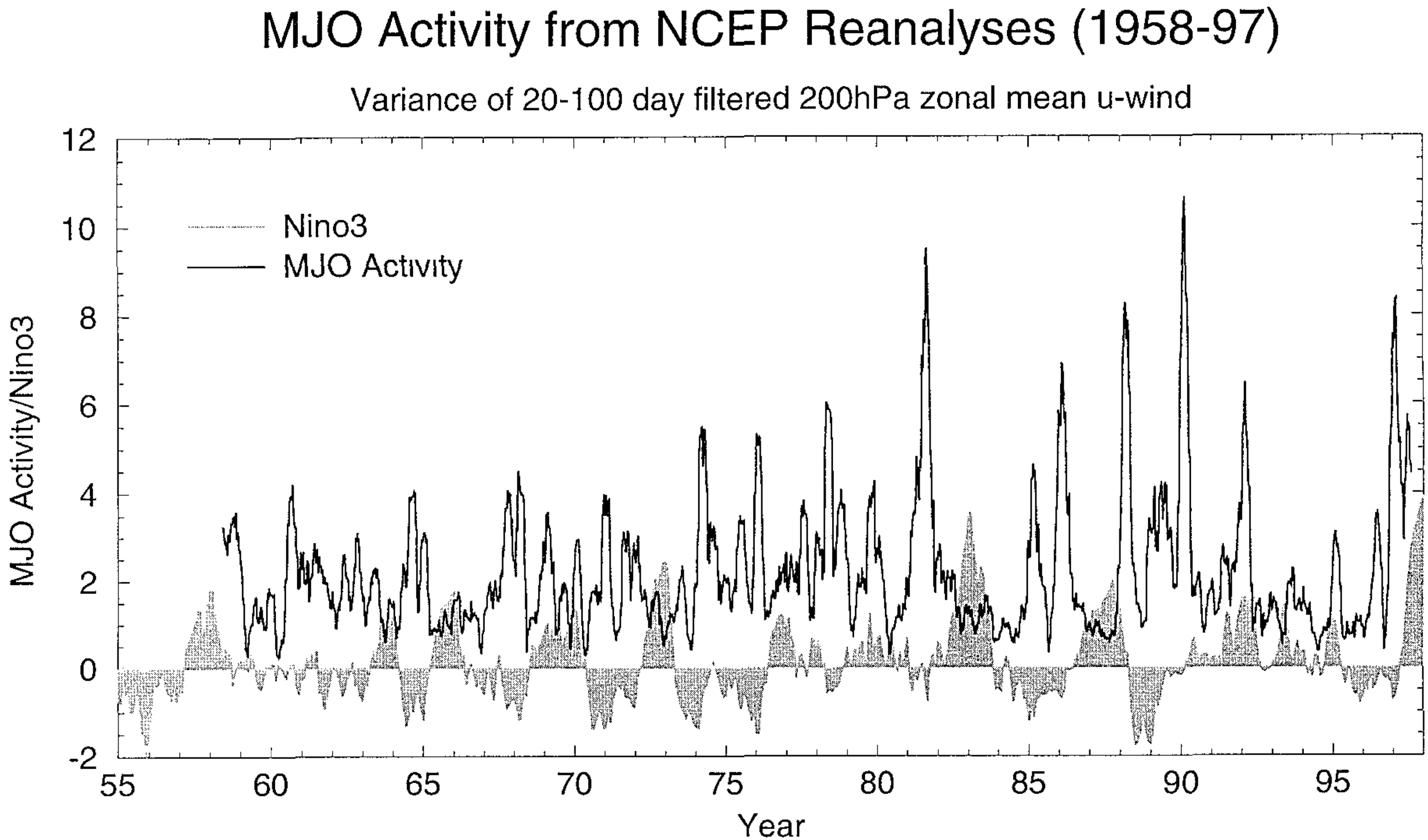
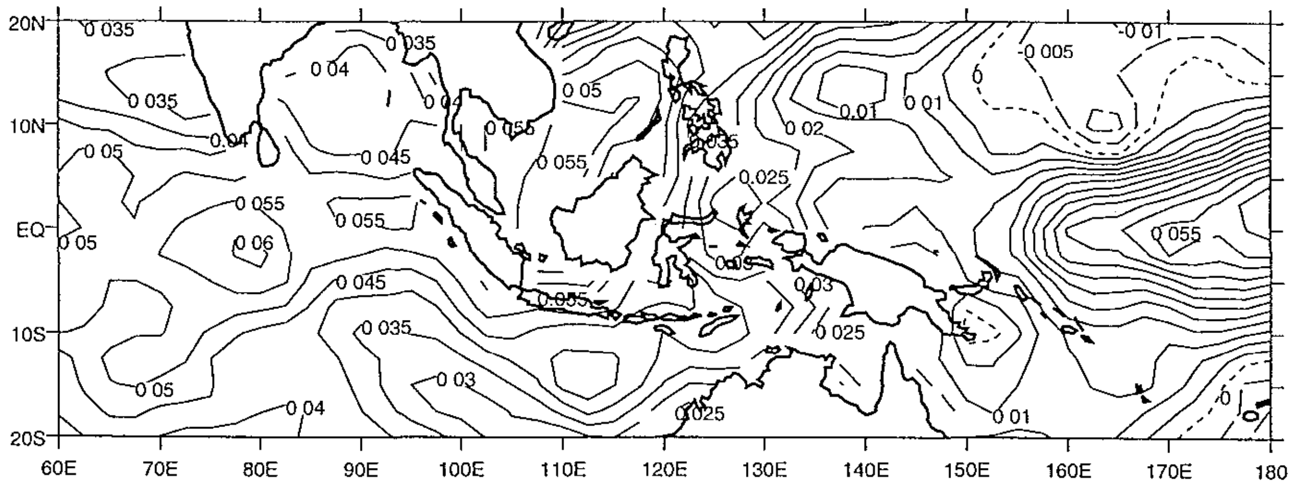

MJO Activity from NCEP Reanalyses (1958-97)
Variance of 20-100 day filtered 200hPa zonal mean u-wind
Nino3
MJO Activity
MJO Activity/Nino3
Year
12
10
8
6
4
2
0
-2
55
60
65
70
75
80
85
90
95

Figure 7

EOF1 of seasonally detrended monthly mean SSTs: 1958-97



Time series of the first principal component (PC1)

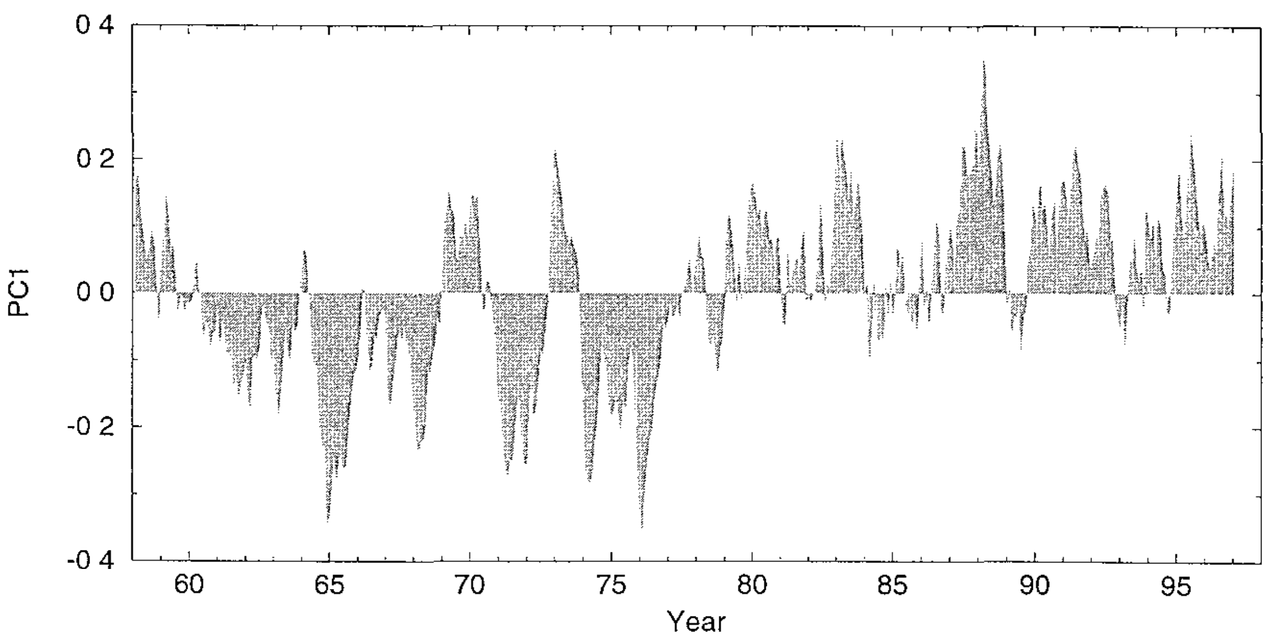


Figure 8

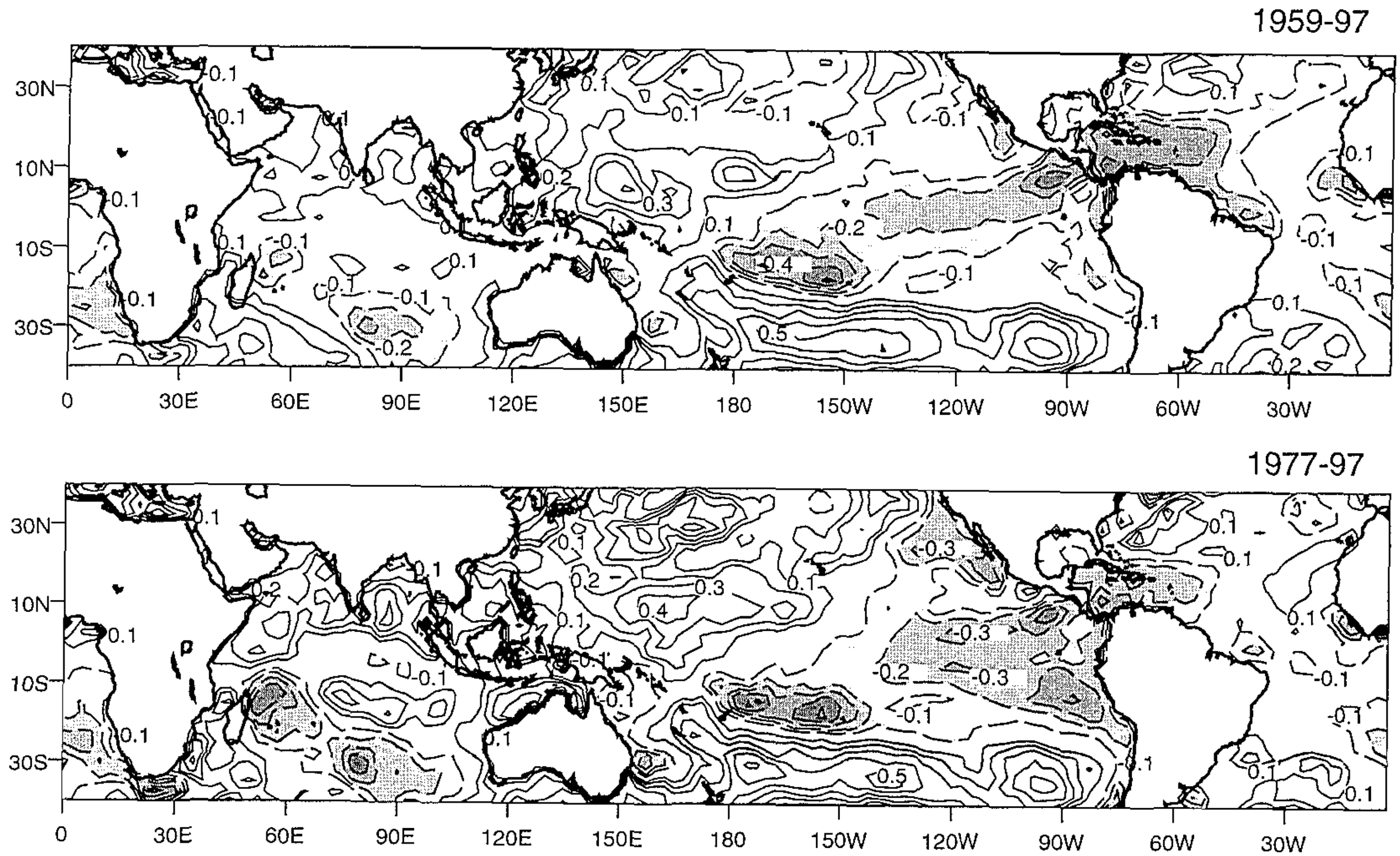

1959-97
30N
10N
10S
30S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
1977-97
30N
10N
10S
30S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W

Figure 9

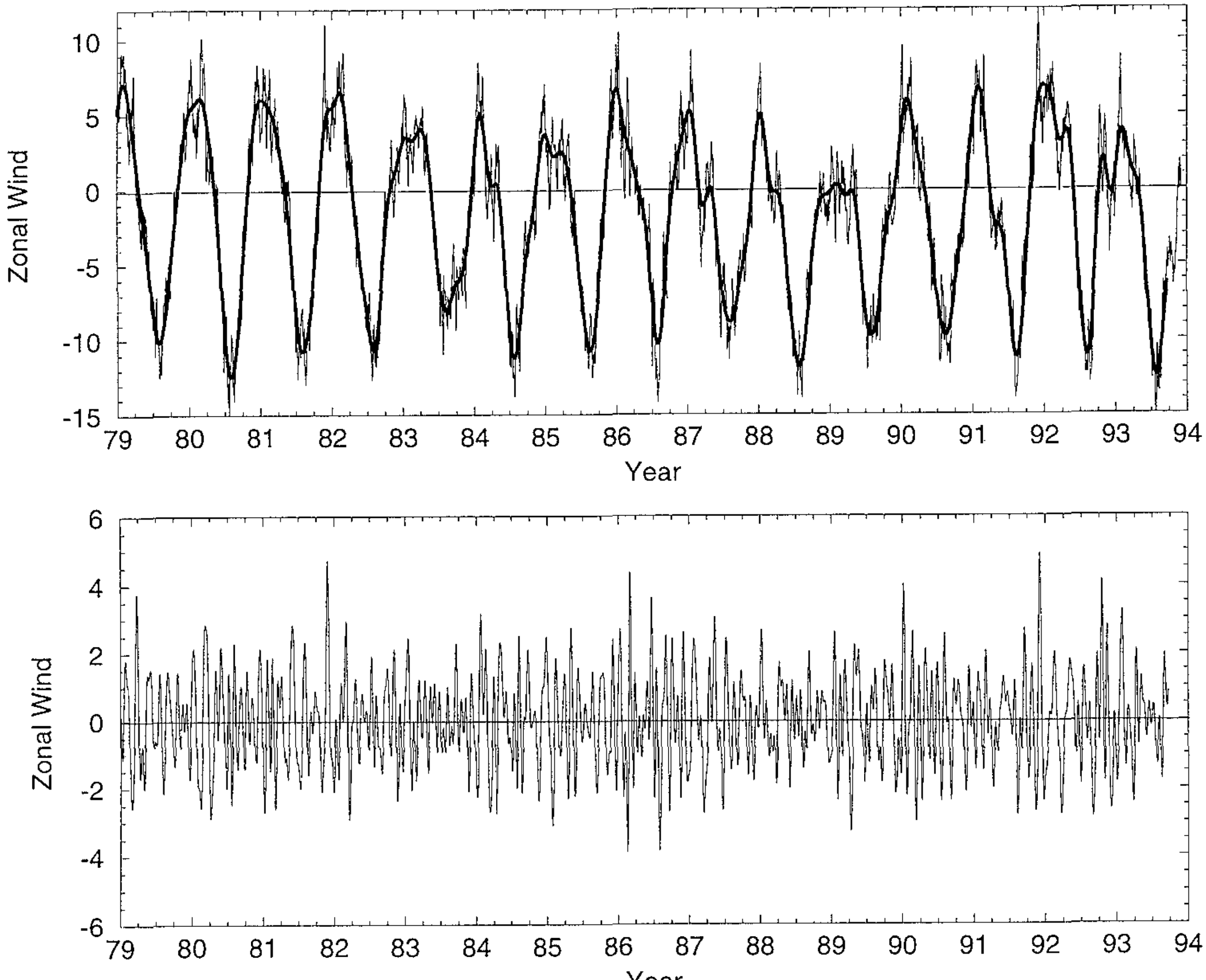

10
5
0
-5
-10
-15
Zonal Wind
79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94
Year
6
4
2
0
-2
-4
-6
Zonal Wind
79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94
Year

Figure 10

Interannual Variability of MJO Index

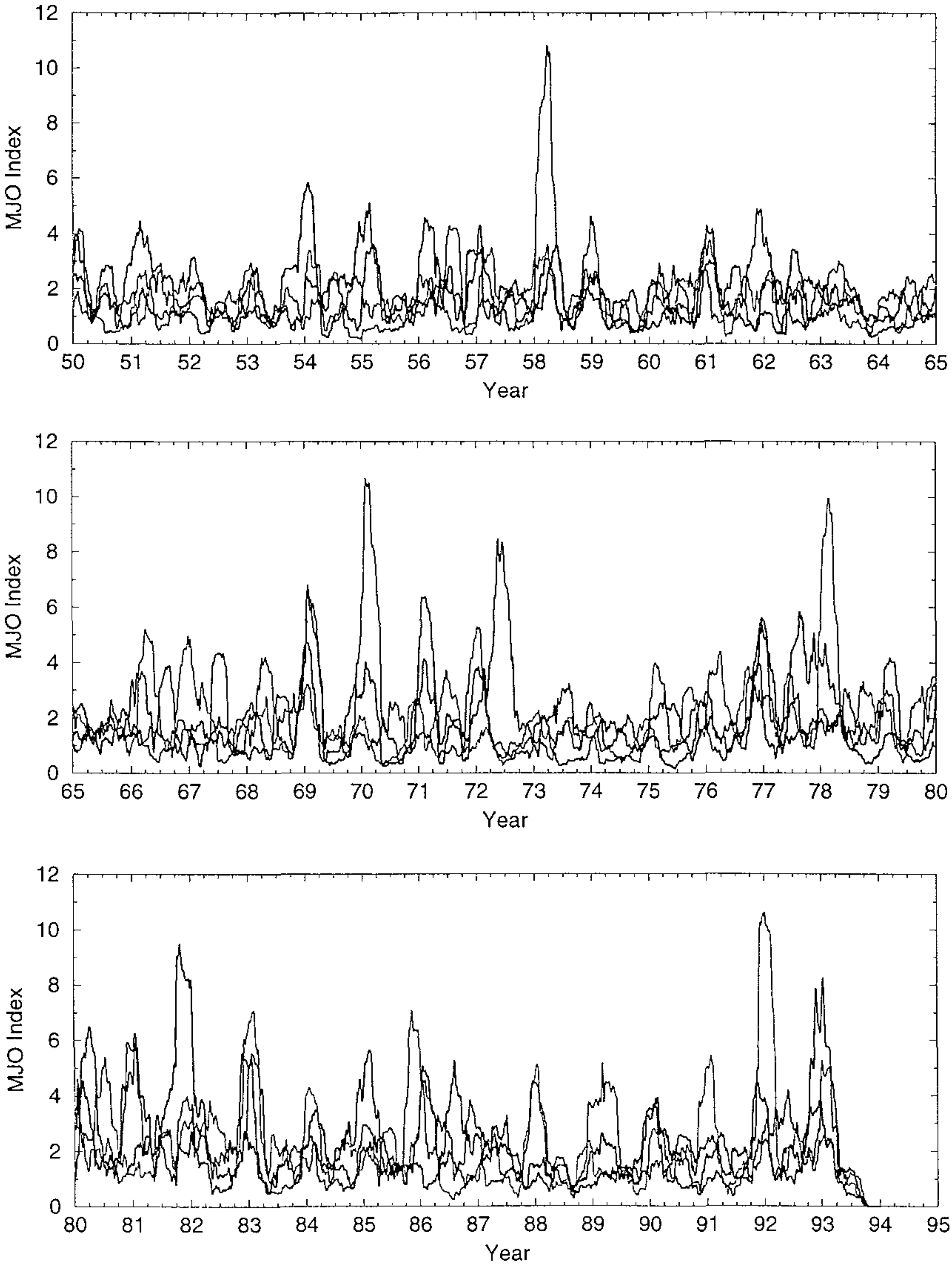


Figure 11

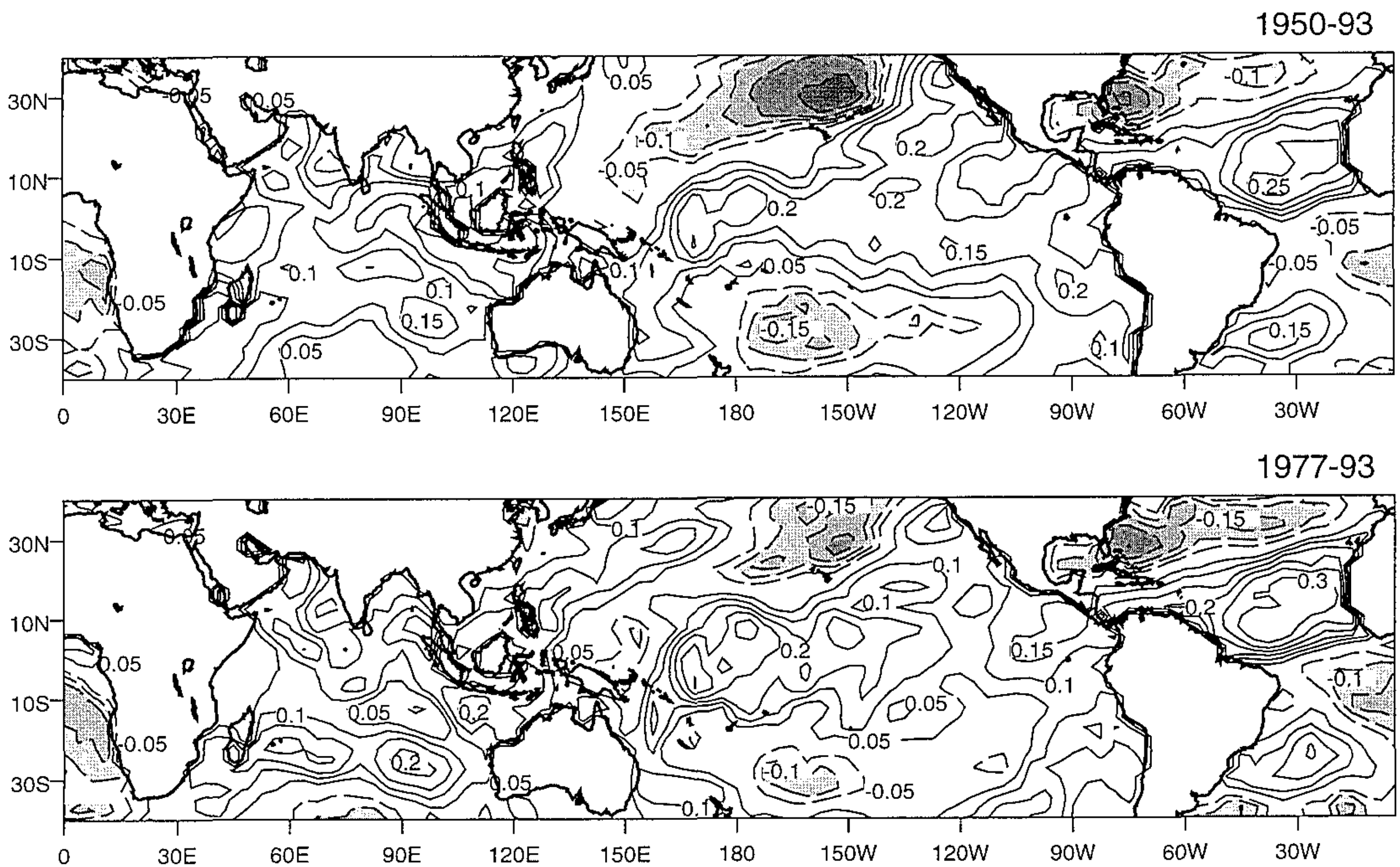

1950-93
1977-93
30N
10N
10S
30S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W

Figure 12

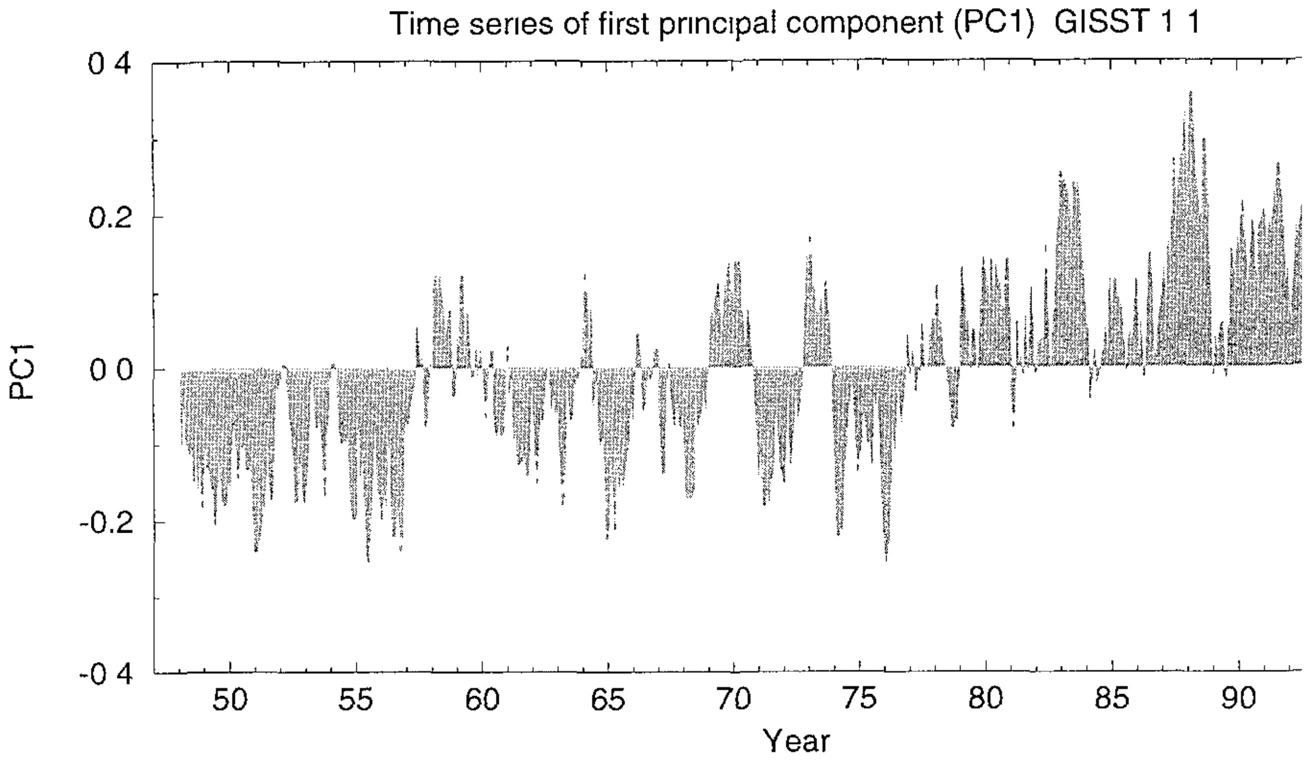

Time series of first principal component (PC1) GISST 1 1
0 4
0.2
0 0
-0.2
-0 4
PC1
50
55
60
65
70
75
80
85
90
Year

Figure 13

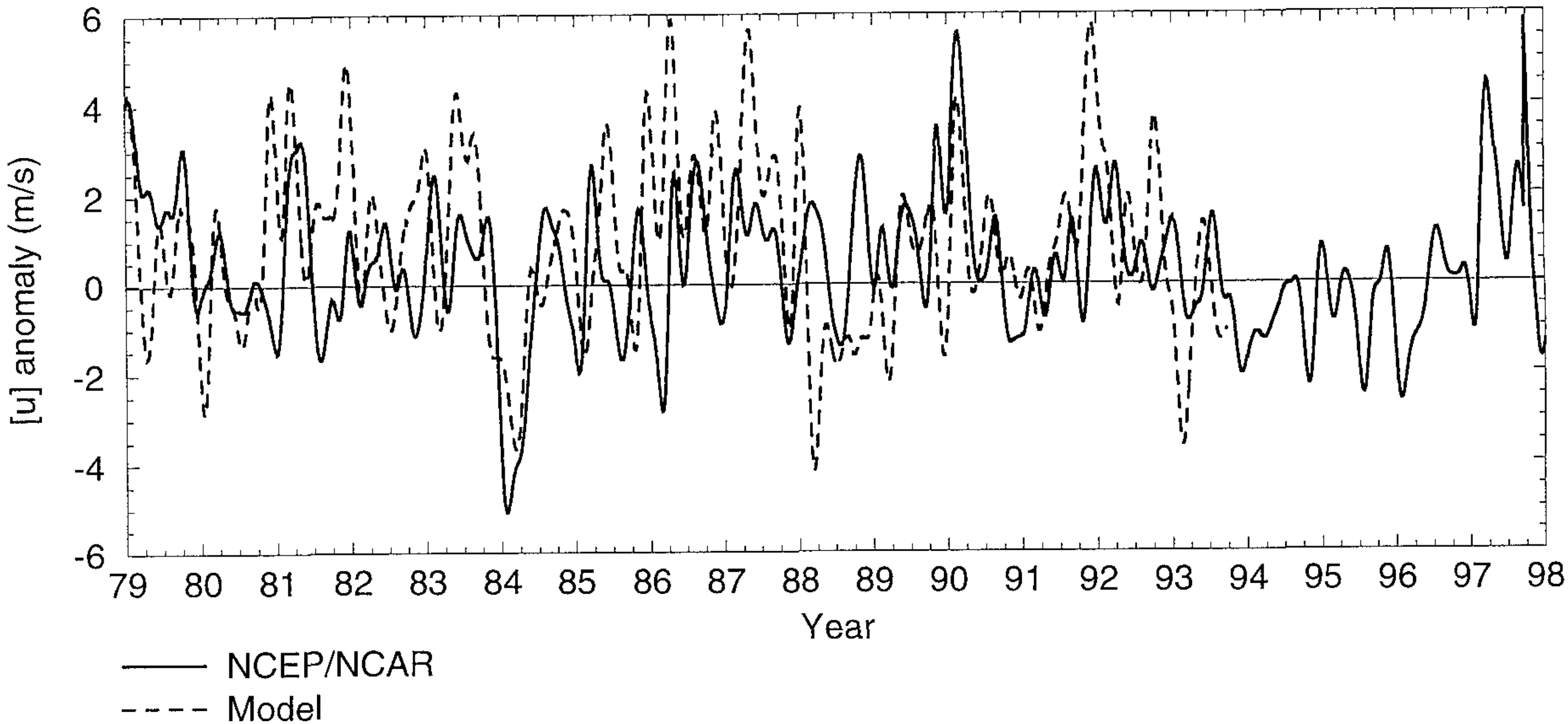
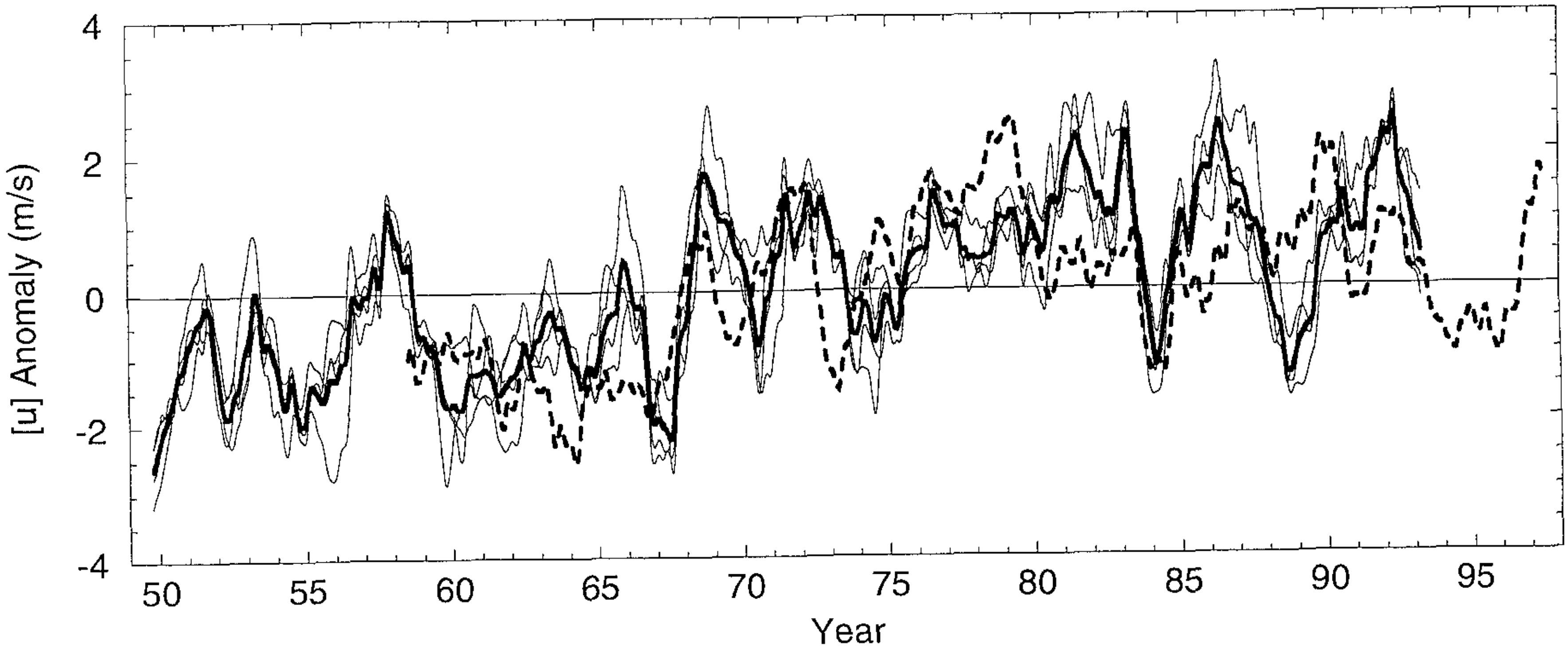

6
4
2
0
-2
-4
-6
[u] anomaly (m/s)
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
Year
NCEP/NCAR
Model

Figure 14



Ensemble member
Ensemble Mean
NCEP/NCAR

Figure 15

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