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Intraseasonal Variability of the Atmosphere-Ocean Climate System

MODELLING THE MADDEN JULIAN OSCILLATION

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1. Introduction

The MJO has long been an aspect of the global climate that has provided a tough test for the climate modelling community. Since the 1980s there have been numerous studies of the simulation of the MJO in atmospheric general circulation models (GCMs), ranging from Hayashi and Golder (1986, 1988) and Lau and Lau (1986), through to more recent studies such as Wang and Schlesinger (1999) and Wu et al. (2002). Of course, attempts to reproduce the MJO in climate models have proceeded in parallel with developments in our understanding of what the MJO is and what drives it. In fact, many advances in understanding the MJO have come through modeling studies. In particular, failure of climate models to simulate various aspects of the MJO has prompted investigations into the mechanisms that are important to its initiation and maintenance, leading to improvements both in our understanding of, and ability to simulate, the MJO.

Most of the early studies concentrated on the ability of models to simulate the signal of the MJO in the upper level winds, partly because these were the fields in which the MJO was originally identified in observations and partly because the dynamical signal of the MJO has often been more reliable in GCMs than its convective signal. Many quite simple GCMs with coarse resolution were shown to produce a peak at approximately the right frequency in the spectrum of upper tropospheric wind variability, along with many of the characteristics of the observed oscillation (e.g. Slingo and Madden 1991, Hayashi and Golder 1993). Furthermore, these studies showed that the simulated oscillation resembled the observed structure of a Kelvin wave coupled to a forced Rossby wave, and with the typical baroclinic structure in the vertical (e.g. Knutson and Weickmann 1987, Matthews et al. 1999). However there remained some substantial deficiencies; in particular, the periodicity of the simulated oscillation tended to be too short, nearer 25-30 days than 40-50 days, and the eastward propagation of the convective anomaly across the warm pool of the Indian and West Pacific Oceans was poorly simulated.

In the 1990s, a comprehensive study of the ability to simulate the MJO by the then state-of-the-art atmospheric models was carried out by Slingo et al. (1996) as part of the first Atmospheric Model Intercomparison Project (AMIP I; Gates et al. 1999). In that study, the following key questions for the simulation of the MJO were addressed:

- Can characteristics of the convective parameterization, such as the vertical profile of the heating, the closure (e.g. moisture convergence), be identified, which might influence the existence of intraseasonal variability?
- Can the behavior of the MJO be related to the incidence of synoptic variability, and/or vice versa?
- What seasonal and interannual variability in the activity of the MJO is simulated? How does it compare with reality?
- How does the intraseasonal oscillation depend on aspects of a model's basic climate?

Slingo et al. (1996) showed that, although there were GCMs that could simulate some aspects of the MJO, all the models in their survey were deficient in some respect. In particular, the period of the oscillation was too fast in many models, and the amplitude of the MJO signal in the upper level winds was often too weak. No model was able to capture the pronounced spectral peak associated with the observed MJO. In reality, the MJO is strongest and most coherent in northern winter/spring (see Fig. 11.1) whereas many models showed no seasonality for the MJO. Furthermore, as the envelope of enhanced convection associated with the variations in the upper wind field develops over the Indian Ocean and propagates eastwards into the west Pacific, the propagation speed of the oscillation is observed to slow down. Many models failed to capture this geographical dependence. In an extension of this study, focusing on the most skilful models in AMIP I, Sperber et al. (1997) showed that, at best, the models produced a pattern of standing oscillations, with convective anomalies developing and decaying over the Indian Ocean on intraseasonal timescales, with out-of-phase oscillations occurring over the west Pacific. A more recent, limited intercomparison by Wu et al. (2002) has shown that models are still unable to reproduce the observed concentration of power at the 40-50 day timescale. However, progress in simulating the MJO is being made. At a workshop on simulation and prediction of subseasonal variability in 2003, most of the models presented were able to simulate at least some aspects of the MJO (Waliser et al, 2003a), with more details of MJO simulation by coupled ocean atmosphere models and AMIP II models described in AchutaRao et al. (2004). In contrast to the study of Slingo et al. (1996), some of the modeling results presented at this workshop showed an MJO that was actually too strong or propagated more slowly than the observed oscillation. It is probably true to say that as our understanding of the MJO increases we are setting our GCMs more stringent tests in terms of what constitutes a 'good' MJO simulation. Even so, the questions posed in 1996 by Slingo et al. are still very relevant.

The initial focus of this chapter will be on modeling the MJO during northern winter, when it is characterized as a predominantly eastward propagating mode and is most readily seen in observations. Aspects of the simulation of the MJO will be discussed in the context of its sensitivity to the formulation of the atmospheric model, and the increasing evidence that it may be a coupled ocean-atmosphere phenomenon. Later, we will discuss the challenges regarding the simulation of boreal summer intraseasonal variability, which is more complex since it is a combination of the eastward propagating MJO and the northward propagation of the tropical convergence zone. Finally some concluding remarks on future directions in modeling the MJO and its relationship with other timescales of variability in the tropics will be made.

2. The MJO in boreal winter

The preferred boreal winter seasonality of the MJO can be seen in an index of MJO variability based on the near-equatorial zonal wind at 200hPa, which was first introduced by Slingo et al. (1996) to provide a preliminary measure of MJO variability in models (Fig. 11.1). This index also shows that there is substantial interannual variability in the activity of the MJO, which Slingo et al. (1999) found was not strongly related to sea surface temperatures (Fig. 11.1 also includes the time-series of the Niño-3 region SST anomaly). This lack of predictability was also seen in a 4-member ensemble of 45 year integrations with the Hadley Centre climate model (HADAM2a), forced by observed SSTs for 1949-93, suggesting that the interannual behaviour of the MJO is not controlled by the phase of El Niño and would appear to be mainly chaotic in character. This may have important implications for the predictability of the coupled system through the influence of the MJO on westerly wind activity and hence on the development and amplification of El Niño (e.g. McPhaden 1999; Lengaigne et al. 2004).

Also evident in Fig. 11.1 is a marked decadal change in the activity of the MJO. 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. However, as described by Slingo et al. (1999), the ensemble of integrations with the Hadley Centre model were able to reproduce the low frequency, decadal timescale variability of MJO activity seen in Fig. 11.1. The activity of the MJO is consistently lower in all realizations prior to the mid 1970s, suggesting that the MJO may indeed become more active as tropical SSTs become warmer with implications for the effects of global warming on the coupled tropical atmosphere-ocean system.

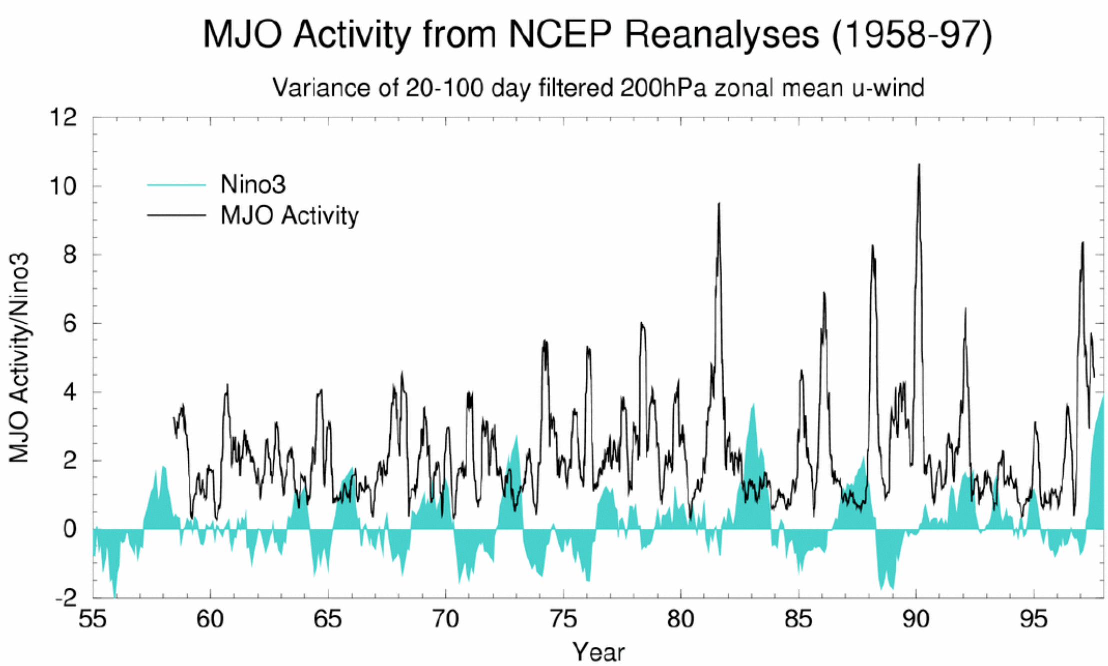

Figure 11.1: Interannual variability in the activity of the MJO as depicted by the time series of the variance (m^2s^{-2}) of the 20-100 day band pass filtered zonal mean zonal wind from the NCEP/ NCAR Reanalysis for 1979-97. A 100-day running mean has been applied to the variance time series. The lower, shaded curve is the sea surface temperature anomaly (K) for the Niño3 region (5°N-5°S, 90°W-150°W). See Slingo et al. (1999) for more details.

2.1 Sensitivity to the formulation of the atmospheric model

In the 1980s, the resolution of GCMs was low by comparison with the current generation of models, and much of the early success in simulating an eastward propagating mode was achieved with models whose resolution was not sufficient to resolve tropical synoptic systems. Since the active phase of the MJO is often characterized by smaller scale organized convection associated with tropical synoptic systems, this lack of resolution was considered a possible cause for the errors in the simulation of the MJO. In the early 1990s, Slingo et al. (1992) analysed the tropical variability in high-resolution (T106, ~1.1^{o}) simulations with the ECMWF model and showed that the various aspects of tropical synoptic variability, such as easterly waves, could be captured with considerable skill. Their integrations were not long enough, however, to say anything conclusive about the MJO.

In AMIP I, the majority of models were run at resolutions capable of capturing synoptic variability (typically T42, equivalent to a grid of at least 3^{o}, and above). However, the results from the study by Slingo et al. (1996) suggested that horizontal resolution did not play an important role in determining a model's intraseasonal activity. Even at much higher resolutions, up to as much as T576, recent evidence from ECMWF suggests no improvement in the simulation of the MJO (Jung and Tompkins 2003). Hence at this stage there is no clear evidence that increasing the horizontal resolution in the atmospheric model will improve the simulation of the MJO, possibly because of more fundamental errors in representing convection and its interaction with dynamics. Support for this hypothesis has come recently from the studies of Grabowski (2003) and Randall et al. (2003) in which the convective parametrization has been replaced by a 2-dimensional cloud-resolving model – the 'cloud-resolving convective parametrization' approach. By representing the interaction between the convective clouds and the dynamics more completely, their studies have shown dramatic improvements in the organization of convection on both synoptic and intraseasonal timescales. Whilst these are very preliminary results, and the use of a cloud resolving model in this way is currently prohibitively expensive, they do provide important insights into fundamental aspects of organized convection in the tropics and how to address sub-gridscale processes.

Even though there is no compelling evidence to suggest that horizontal resolution is important for the simulation of the MJO, this appears not be the case for vertical resolution. Experiments with the Met Office Unified Model (UM, version HadAM3) using two different vertical resolutions (19 and 30 levels) have shown significant differences in the amount of variability in the tropical upper tropospheric zonal wind component associated with the MJO (Inness et al. 2001). Most of the extra levels were placed in the middle and upper troposphere, decreasing the layer thickness in the mid-troposphere from 100hPa to 50hPa, and giving a much better representation of the temperature and humidity structure around the freezing level. The model results suggested a change in the temporal organization of convection which was investigated further using an aqua-planet version of the UM. These experiments, described in detail in Inness et al. (2001), showed that when the vertical resolution was increased in the UM, the spectrum of tropical cloud top heights changed from a bimodal to a tri-modal distribution, with a third peak in the mid-troposphere, near the freezing level. Associated with periods when these mid-level clouds were dominant, the detrainment from these clouds significantly moistened the mid-troposphere. In comparison, the 19-level version of the model shows no evidence of a tri-modal distribution in convection and no such moistening events.

Many conceptual models of tropical convection are based on a bimodal cloud distribution, emphasizing shallow ‘trade-wind’ or boundary layer cumuli and deep cumulonimbi. However, TOGA COARE results have shown the dominance of cumulus congestus clouds, and point to a tri-modal cloud distribution in which the freezing level inversion is the key. Observational studies have shown that, during the suppressed phase of the MJO, tropical convection is dominated by clouds that terminate around the stable layer at the 0^{o}C level (Johnson et al. 1999), and that these clouds provide a source of moisture to the mid-troposphere (Lin and Johnson 1996). Inness et al. (2001) argued that the development of a stable layer around the tropical melting level, which is frequently observed over the tropical oceans, acts to reinforce the transition from the enhanced convective phase to the suppressed phase of the MJO. Subsequently, the moistening of the mid-troposphere during the suppressed phase acts to reinforce the transition back to the active phase. This is consistent with the ‘recharge-discharge’ theory for the MJO proposed by Bladé and Hartmann (1993) in which the MJO timescale may be set by the time it takes for the moist static energy to build up following the decay of the previous convective event. It may be that the recharging of the moist static energy is achieved in part by the injection of moisture into the mid-troposphere by the cumulus congestus clouds that dominate during the suppressed phase of the MJO.

The appearance of these congestus clouds has been postulated as the reason for the improvement in the simulation of the MJO in the 30-level version of the UM. This is shown to be partly due to improved resolution of the freezing level and of the convective processes occurring at this level. However, the results also suggest that convection and cloud microphysics schemes must be able to represent cumulus congestus clouds which, being neither shallow nor deep cumulus as well as often weakly precipitating, tend not to be explicitly represented in current schemes. In addition, this study has highlighted the importance of understanding and modeling the suppressed phase of the MJO; over the last two decades most of the attention has been given, understandably, to the active phase of the MJO, but with limited success. Further evidence of the importance of cumulus congestus in the life-cycle of the MJO comes from a theoretical and simple modeling study by Wu (2003). This study presents a 'shallow CISK, deep equilibrium' mechanism for the interaction of convection and large scale circulations in the tropics, emphasizing the role of the heating by congestus clouds as a precursor to the outbreak of deep convection corresponding to the active phase of the MJO.

The results of Inness et al. (2001) highlighted the importance of vertical resolution, in line with the study of Tompkins and Emanuel (2000), as well as the need to properly represent the tri-modal structure of tropical convection. The importance of the cumulus congestus stage of tropical convection is being stressed here as a potentially important ingredient for the MJO. This means that vertical resolution in the free troposphere must be adequate to resolve the formation of the freezing level inversion and the cooling associated with melting precipitation.

That the MJO is intimately linked to convection is undeniable, and numerous modeling studies have demonstrated that changes to the convection scheme can produce radical changes in the simulation of the MJO. Slingo et al. (1994) replaced the Kuo convection scheme (Kuo, 1974; closed on moisture convergence) by the convective adjustment scheme of Betts and Miller (Betts, 1986; closed on buoyancy) and showed extreme sensitivity in the representation of organized tropical convection at synoptic to intraseasonal timescales, with the Kuo scheme unable to capture realistic levels of tropical variability. This suggested that a dependence of convective activity on moisture convergence might be a factor in the poor simulation of the MJO. This was further supported by Nordeng (1994), who showed that when the moisture convergence dependence of the ECMWF convection scheme was replaced by a buoyancy criterion, there was a marked improvement (i.e. increase) in transient activity in the tropics of the ECMWF model. More recently, the closure of the convection scheme of the Australian Bureau of Meteorology Research Center's seasonal prediction GCM has been modified from moisture convergence to CAPE relaxation, with a resulting increase in eastward moving power at MJO frequencies (M. Wheeler in Waliser et al. 2003a). At a broader level, Slingo et al. (1996) also suggested that those models in AMIP I with a reasonable level of intraseasonal activity used convection schemes that were closed on buoyancy rather than moisture supply. However, as Wang and Schlesinger (1999) demonstrated, it is possible to change the strength of the MJO substantially by modifying the particular closure used within the convection scheme, as well as the fundamental design of the convection scheme itself. But as they point out, some configurations of the convection schemes did not produce realistic mean climates, which as will be discussed later, can compromise the simulation of the MJO. Studies such as that of Lee et al (2003) have also demonstrated that considerable improvements to the simulation of the MJO can be brought about by modifications to the convective parametrization. In this case, the imposition of a minimum entrainment rate for deep convective plumes in the Arakawa-Schubert convection scheme (Arakawa and Schubert, 1974, Tokioka et al. 1988) in an aquaplanet configuration of the Seoul National University GCM resulted in a much stronger MJO-like signal.

Although there has recently been a move away from convection schemes that are closed on moisture convergence towards those based on buoyancy considerations, difficulties still remain. Many schemes use an equilibrium approach to convection, which assumes that instabilities are removed completely at each timestep. Sensitivity experiments with non-equilibrium closures suggest that improvements in the intraseasonal organization of convection can be achieved, but often at the expense of the quality of the mean climate. Indeed, separating the effects of the changes to the convection scheme on the organization of convection, from the effects on the mean climate of the tropics has been notoriously difficult. For example, Inness and Gregory (1997) showed that the inclusion of the vertical transport of momentum by the convection scheme considerably weakened the upper tropospheric signal of the MJO in the UM, possibly due to changes in the basic state winds in tropical latitudes.

Although much of the focus of attention for the simulation of the MJO has been on the convective parametrization, there are other aspects of the physics that deserve attention. For example, a study by Salby et al. (1994) has suggested that the oscillation may be very sensitive to boundary layer friction in which the sympathetic interaction between the convection and the large scale circulation, through the process termed ‘frictional wave-CISK’, can explain many aspects of the observed behavior of the MJO in the eastern hemisphere. Due to frictional effects the surface convergence is shifted some 40-50^{o} to the east of the heating, towards low pressure and in phase with the temperature anomaly associated with the Kelvin wave. This study also emphasized the importance of the Rossby gyres generated by the heating. In the amplifying phase of the MJO their position is such as to reinforce the moisture convergence to the east of the heating, so providing the necessary conditions for the heating to amplify and propagate eastwards. Salby et al. (1994) showed that their solutions were very sensitive to the boundary layer friction, suggesting that this may be an important factor in GCMs, but one which, so far, has not been pursued. However, Sperber et al. (1997) investigated the role of wind induced surface heat exchange (WISHE; Emanuel, 1987) and frictional wave CISK in the MJO as simulated by the most skilful models in AMIP I, and concluded that neither mechanism was represented by the models.

With the low-level moisture convergence leading the convection, there is a pronounced westward vertical tilt in the divergence, vertical velocity, zonal wind, and specific humidity, as demonstrated by Sperber (2003) and Seo and Kim (2003) using the NCEP/NCAR reanalysis. The strongest zonal inflow into the convective region occurs in the free troposphere between 600-700hPa. The conditions to the east of the center of convection promote the eastward propagation of the MJO, while to the west they erode the convection. Thus, free-tropospheric interactions are also an essential component of MJO that models need to represent. The ability of the models to represent these features will be sensitive to the simulated diabatic heating profile, and thus to the afore-mentioned sensitivities to convection scheme and vertical resolution. Unfortunately, such detailed analyses of models are not the norm due to extensive archive of data required. However, further progress in understanding a models ability to capture the MJO will necessitate more comprehensive model output to become routine.

In a recent paper, Raymond (2001) suggested that cloud-radiation interaction might be important for the simulation of the MJO. Slingo and Madden (1991), in their study of the MJO simulated by the NCAR Community Climate Model, investigated the role of cloud longwave forcing in the behavior of the MJO. They showed that cloud-radiation interaction had little effect on the periodicity of the MJO and its basic characteristics. Without cloud-radiation interaction, the simulated MJO was slightly more regular. However, this issue probably deserves revisiting with the current models that have a more sophisticated representation of cloud microphysics. In fact, this area is indeed being investigated more fully in the context of the 'cloud-resolving convective parametrization' approach discussed earlier in this chapter (e.g. Grabowski and Moncrieff, 2002). In this approach, the convective parametrization is replaced by a cloud resolving model in each grid column and so the representation of cloud microphysics is far more detailed than in a conventional GCM. Initial results do indicate that the interaction of the clouds and radiation does indeed have a part to play in the large-scale organization of convection.

2.2. Modeling the MJO as a coupled ocean-atmosphere phenomenon

One of the biggest advances in modeling the MJO during the last few years has been in the recognition that it almost certainly involves coupling with the ocean, as discussed in chapter 8. There is now convincing evidence from observations that the MJO interacts with the upper ocean in such a way for it to be a coupled phenomenon, and which may therefore require an interactive ocean system for its proper simulation. In a comprehensive analysis of observational and reanalysis data, Woolnough et al. (2000) showed that, for the Indian Ocean and West Pacific, a coherent relationship exists between MJO convection, surface fluxes and sea surface temperature (SST), in which the SSTs are warmer than normal about 10 days prior to, and east of, the maximum in convective activity (Fig. 11.2a). This warming is associated with increased solar radiation, reduced surface evaporation and light winds which reduces vertical mixing. To the west of the convective maximum, the SSTs cool due to reduced solar radiation and enhanced evaporation associated with stronger winds. A key requirement for the observed temporal and spatial phase relationship between the latent heat flux, winds and convection is the presence of a surface westerly basic state, an issue that emerges later as being crucial for the improved simulation of the MJO in coupled models. In addition to the SST anomaly pattern, Fig. 11.2 also shows the phasing of the surface flux and wind stress anomalies relative to the convective maximum.

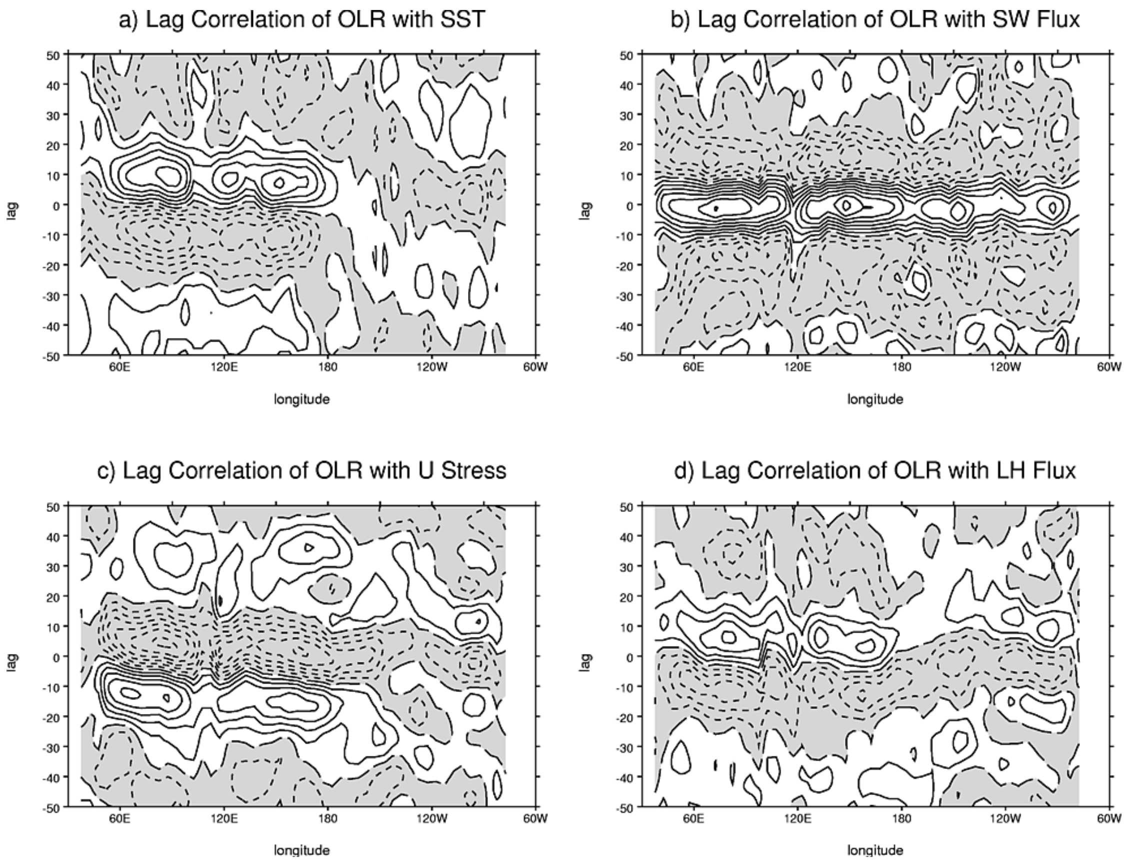

Figure 11.2: Lag correlations between observed OLR (convection) and surface fields: (a) sea surface temperature (SST), (b) shortwave radiation, (c) zonal wind stress and (d) latent heat flux. Negative lags indicate that the convection lags the surface field, positive lags indicates that the convection leads the surface fields. The sign convention is such that positive correlations indicate that enhanced convection (a negative OLR anomaly) is correlated with a negative SST anomaly, reduced shortwave radiation at the surface, enhanced evaporation or an easterly wind stress anomaly. From Woolnough et al. (2000).

Having established that the surface fluxes and winds associated with the MJO can force intraseasonal variations in the SSTs, which can typically reach 1K in individual events, it then needs to be confirmed that the atmosphere can respond to these SST variations. In a related study, Woolnough et al. (2001) therefore used the observed SST perturbations associated with the MJO to form the basis of a series of experiments with the aquaplanet version of the UM to investigate firstly the organization of tropical convection by these intraseasonal anomalies, and secondly, how this organization depends on the temporal behavior of these SST anomalies. The study showed that the boundary layer humidity adjusts rapidly to the presence of the SST anomaly. However, the free atmosphere takes longer to adjust. Initial convective plumes triggered by the presence of warm SSTs are rapidly eroded by entrainment of dry air in the free troposphere and so terminate relatively low down in the troposphere. However, the detrainment of the terminating plumes moistens the atmosphere allowing subsequent convective plumes to penetrate further before decaying. Eventually the atmosphere is moist enough to support deep convection through most of the depth of the troposphere. This type of pre-conditioning behavior means that the most intense convection occurs, not directly over the warm SST anomaly, but to the west over the maximum gradient in SST between the warm and cold anomalies, as observed in the MJO. The timescale of about 5 days for the preconditioning of the tropical atmosphere for deep convection has recently been confirmed in a detailed study of reanalysis data by Sperber (2003). Associated with this adjustment timescale, the experiments of Woolnough et al. (2001) also showed that intraseasonal SST anomalies could potentially organize convection in a manner that favors the longer timescales (~60 days), typical of the observed MJO, and which produces a phase relationship between the convection and SST, consistent with the observed structure over the Indian and West Pacific Oceans.

Sperber et al. (1997) had already suggested that a possible reason for the lack of realistic propagation of convective anomalies in atmospheric models used in AMIP I was that the MJO may be, at least in part, a coupled mode. The results of Woolnough et al. (2000, 2001) appeared to support this hypothesis. Flatau et al. (1997) also proposed that the eastward propagation of MJO convection might involve a coupled mechanism, and performed a simple numerical experiment to test their hypothesis. Using a low resolution (spectral R15) GCM, configured as an aqua-planet model, they modeled the dependence of SST on surface fluxes empirically by relating SST fluctuations to changes in the strength of the low-level winds, based on observed SST changes and wind speeds from drifter buoys in the tropical Pacific. Their results showed that oscillations in the low level winds on intraseasonal timescales became more organized when the variations of SST with wind speed were included, producing a coherent, eastward propagating signal which resembled the MJO in some respects.

A similar modelling study was carried out by Waliser et al. (1999), but using a more complex GCM and a more realistic parametrization of SST anomalies in the tropics, based on a slab ocean model of fixed depth in which SST anomalies developed in association with changes in net surface heat flux according to the formula:

$$dT'/dt = F'/(\rho C_p H) - \gamma T'$$

Here T' is the SST anomaly, F' is the surface flux anomaly, H is the depth of the mixed layer (fixed at 50m) and γ is a damping factor, set to (50 days)$^{-1}$. Changes in SST due to this formula were small, however, being of the order of 0.1-0.15^{o}C and were due largely to changes in the latent heat flux ahead of and behind the convective region, and to changes in the shortwave flux associated with the variations in convective cloudiness. It is worth noting that in their study the use of a fixed mixed layer depth underestimated the SST variability associated with the MJO since the warming during the suppressed phase is, in reality, strongly amplified by the shoaling of the mixed layer during light wind conditions (e.g. Weller and Anderson 1996). Nevertheless, their results showed that the MJO simulation was improved in a number of respects. The period of the oscillation slowed down to be closer to the observed period, the variability of upper level winds and convective activity on intraseasonal timescales became stronger, the number of MJO events occurring during northern hemisphere winter and spring increased significantly and the phase speed of the oscillation slowed in the eastern hemisphere in association with more organized convection.

The results of Waliser et al. (1999) were very encouraging and suggested that a more comprehensive and realistic approach to simulating the coupled aspects of the MJO might be fruitful. However, there have only been a limited number of studies of the MJO in coupled GCMs in the literature. There are several reasons for this. Until quite recently the cost of running coupled GCMs has been prohibitively high for many research centers and so their use had been limited to a few institutes. Secondly, the development of coupled GCMs has historically been motivated by the requirements of long term climate prediction and, more recently, seasonal prediction, so the ability of models to capture variability on timescales of less than a season has not been a primary consideration to the groups involved. Thirdly, it has been only recently that coupled GCMs have been developed without the need for flux-adjustment to maintain a stable mean climate (e.g. Gordon et al. 2000), and there had been concerns that the flux adjustment might compromise the intraseasonal variability of the coupled system.

Initial studies by Gualdi et al. (1999) and Hendon (2000) of the MJO in fully coupled models concluded that an interactive ocean did not improve the simulation. Instead they found that accompanying changes in the mean climate of the model and deficiencies in the representation of surface flux anomalies were the main factors affecting the behavior of the MJO. However, more recently Kemball-Cook et al. (2002), Inness and Slingo (2003) and

Inness et al. (2003) demonstrated that the coupling improves the organization and propagation characteristics of the MJO in comparison with the results from the atmosphere-only models, at least for the boreal winter. Whereas the atmosphere-only model had a predominantly standing oscillation in the convection (Fig. 11.3b), the coupled model produced a more realistic eastward propagating signal (Fig. 11.3a). This was associated with coherent variations in SST, which showed a similar phase relationship with convection as in observations (Fig. 11.2a), with warmer SSTs preceding the maximum in convection by between 5 and 10 days (Fig. 11.3c).

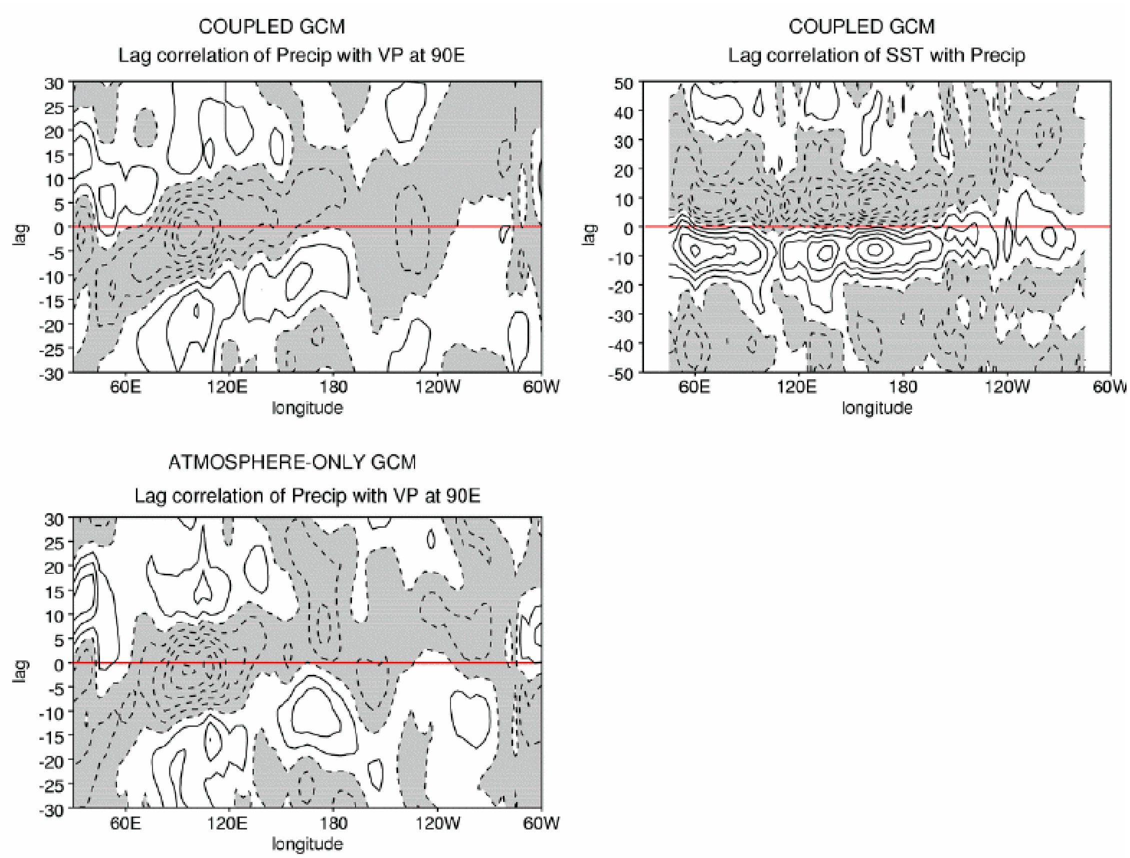

Figure 11.3: Lag correlations between precipitation at every longitude and an index of MJO activity at 90°E, based on the 20-100day filtered 200hPa velocity potential, from (a) a version of the coupled ocean-atmosphere model, HadCM3, and (b) the equivalent atmosphere-only model, HadAM3. (c) shows the simulated lag correlations between the precipitation and SST at every longitude (as in Figure 11.2a) from HadCM3. From Slingo et al. (2003).

Due to the increased number of degrees of freedom in a fully coupled, un-flux corrected GCM, it is much more likely that there will be errors in the basic state than in an atmosphere-only GCM constrained by realistically prescribed SSTs. This has emerged as a crucial factor in the simulation of the MJO in coupled models. In particular the low level climatological westerlies across the Indo-Pacific warm pool associated with the Austral monsoon are critical for the air-sea interaction mechanism of the MJO. It is only when these winds are westerly that the wind perturbations associated with the MJO can give enhanced latent heat fluxes (i.e. cooling of the ocean) to the west of the convection and reduced fluxes to the east (i.e. warming of the ocean). Inness et al. (2003) showed conclusively that the easterly bias over the West Pacific, typical of the majority of coupled models, acts to restrict the eastward propagation of the MJO by disabling the air-sea interaction mechanism. Consequently, improving the mean simulation in coupled models is a major issue facing future improvements in modeling the MJO.

2. Boreal Summer Intraseasonal Variability

A brief discussion of boreal summer intraseasonal variability (BSISV) follows in order to characterize the basic challenges to the modelling community. A more comprehensive discussion of observed variability is presented in Chapters 3 and 4. The BSISV is important because it is intimately related to the active/break cycles of the Asian summer monsoon (Webster et al. 1998), Krishnamurti and Bhalme (1976), Sikka (1980), and Gadgil and Asha (1992). Observed years of below-normal Indian monsoon rainfall tend to be associated with prolonged breaks in the monsoon, and conversely, fewer breaks of shorter duration tend to occur during years of normal or above-normal monsoon rainfall. During northern summer, the MJO is modified substantially by the off-equatorial heating associated with the Asian Summer Monsoon. It has a mixed character of both northward and eastward propagation. Northward propagation of the tropical convergence zone on time scales of 30-50 days over the Indian longitudes was initially identified by Yasunari (1979, 1980) and Sikka and Gadgil (1980), and over the west Pacific by Murakami et al. (1984), and Lau and Chan (1986). Wang and Rui (1990) classified intraseasonal propagating events over the monsoon domain, including isolating northward propagation that occurred independent of eastward propagation. Later, Lawrence and Webster (2002) found that 78% of northward propagating intraseasonal events were accompanied by eastward propagation, and it is mainly on these events that we concentrate. Figure 11.4a shows the composite rainfall from observations corresponding to active convection over India, extending to the southeast into the western Pacific. As this tilted rainband propagates to the east, rainfall occurs further north at a given longitude.

Lau and Peng (1990) proposed that the northward propagation is due to coupled Kelvin wave-Rossby wave interactions. The theory of tropical intraseasonal oscillations is discussed in Chapter 2. The intermediate complexity model of Wang and Xie (1997) replicated the northwest-southeast tilt of the rainband due to Kelvin wave-Rossby wave interactions. Observational evidence that the tilt is due to the emanation of Rossby waves has been found by Annamalai and Slingo (2001), Kemball-Cook and Wang (2001), and Lawrence and Webster (2002). Annamalai and Sperber (2004) used a linear barotropic model forced with heating proportional to the rainfall rate for different phases of the BSISV life-cycle. They were able to reproduce the observed low-level circulation, and showed that the development of the forced Rossby waves could only occur in the presence of easterly zonal shear, as suggested by Lau and Peng (1990) and Wang and Xie (1997). Additionally, they concluded that the intraseasonal variability over the Indian Ocean and the west Pacific are mutually dependent systems. That is, the convection over the west Pacific helps initiate the monsoon break over India, while the Indian Ocean convection can modulate the active and break phase over the west Pacific.

Additionally, low-level moisture convergence is important for maintaining the eastward propagation as it destabilizes the atmosphere ahead of the main center of convection. In the boreal summer, the northward propagation also exhibits the tendency for low-level moisture convergence to lead the convection (Kemball-Cook and Wang 2001). Thus, the mechanisms involved in boreal summer intraseasonal variability are akin to those during the boreal winter MJO. Additionally, over the western north Pacific it has been suggested that subtropical westward propagating low-level convergence anomalies contribute to the northwestward propagation of the rainband (Hsu and Weng 2001). Thus, the complex nature of the BSISV makes it especially challenging to simulate.

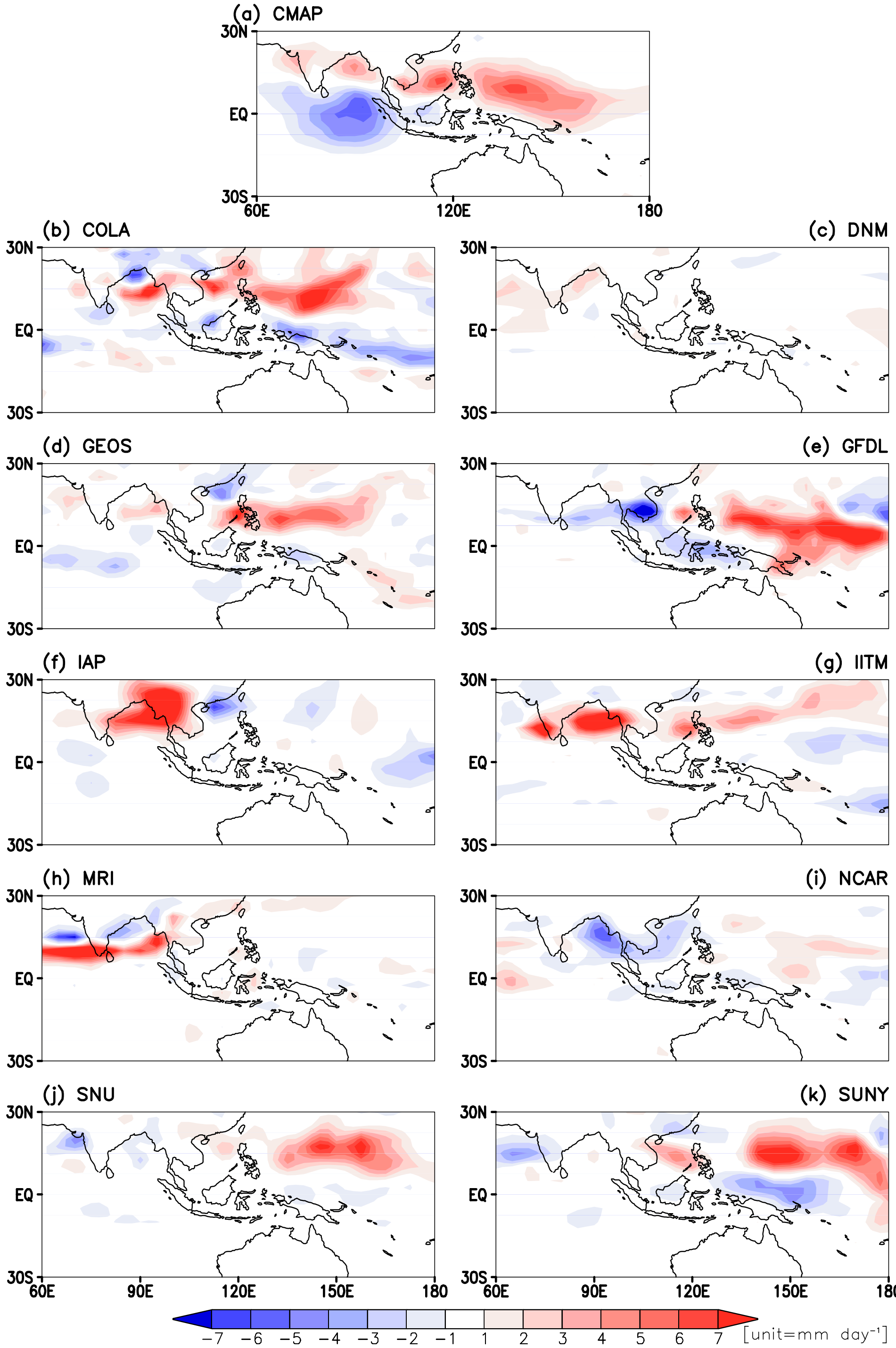

Figure 11.4: Composite BSISV rainfall for days 0~+5 based on identification using extended empirical orthogonal function analysis as per Waliser et al. (2003b). (a) observations (CPC Merged Analysis of Precipitation), and atmospheric general circulation models forced with observed weekly sea-surface temperature (b) COLA, (c) DNM, (d) GEOS, (e) GFDL, (f) IAP, (g) IITM, (h) MRI, (i) NCAR, (j) SNU, and (k) SUNY (after Waliser et al. 2003b).

Modeling studies of BSISV have been relatively limited partly due to the difficulties in simulating both the mean monsoon and its variability (Sperber and Palmer 1996, Sperber et al. 2000). Given the complex orography over the summer monsoon domain, deficiencies in simulating rainfall were noted by Hahn and Manabe (1975) and Gilchrist (1977). Subsequently, numerous studies have evaluated the monsoon sensitivity to horizontal resolution, though most studies concentrated on the time-mean behavior (e.g., Tibaldi et al. 1990). Typical results indicated a better representation of the rainfall along the western Ghats and their downwind rainshadow effect, as well as improvement in the foothills of the Himalayas.

The sensitivity of BSISV to horizontal resolution has been found to be model dependent. Using the Geophysical Fluid Dynamics Laboratory GCM, Hayashi and Golder (1986) found that R30 (~2.3^o) better represented the space-time spectra of rainfall compared to the R15 (~4.5^o) model version. Of special note was the ability of the model to simulate the poleward propagation of rainfall over the monsoon domain, including the observed asymmetry, with the Northern Hemisphere propagation being stronger than that in the Southern Hemisphere. Using a T21 (~5.6^o) model from the European Centre for Medium–Range Weather Forecasts (ECMWF), Gadgil and Srinivasan (1990) found that this model produced northward propagation of the rainbelt over the Bay of Bengal. However, using a later version of the ECMWF model, Sperber et al. (1994) found that T106 (~1.1 degrees longitude and latitude resolution) was needed to represent the northward propagation of the tropical convergence zone and the sudden jump of the Mei-yu front over China. Later work suggested coarser resolution models had similar capabilities (Lau and Yang, 1996, Martin, 1999). Differences among models are mainly associated with the combinations of, improvement of, and the addition of physical parameterizations.

The ability of atmospheric models to simulate the dominant intraseasonal rainfall pattern has remained problematic, as shown in Fig. 11.4. These results from an intercomparison study by Waliser et al. (2003b) demonstrate that models have difficulty in representing the tilted rainband and its propagation characteristics. When the full life-cycle of the dominant mode is considered, only half of the models in the study exhibited any northeastward propagation, and none of the models exhibited any systematic intraseasonal rainfall variability over the Indian Ocean.

In the mid-1990's, modelling studies of boreal summer intraseasonal variability and its possible link to interannual variations outpaced our ability to firmly establish such a link in observations. Fennessy and Shukla (1994) used the Center for Ocean Land Atmosphere (COLA) atmospheric general circulation model to simulate the weak (strong) Indian monsoon of 1987 (1988). They found that the spatial pattern of interannual rainfall difference was nearly identical to the difference due to break and active phases of the monsoon. Ferranti et al. (1997) found a similar result with the ECMWF model in AMIP simulations forced with observed SST for 1979-88. Using canonical correlation analysis (CCA), they found the 850hPa relative vorticity exhibited a common mode of variability on interannual and intraseasonal time scales, being characterized by an alternation of the tropical convergence zone between the tropical Indian Ocean and over the continental landmass, centered at about 15^{o}N. However, the oceanic and continental locations of the tropical convergence zone were regime transitions that were not associated with northward propagating intraseasonal events.

With the advent of reanalysis, it became possible to investigate the link between intraseasonal and interannual variability based on a dynamically consistent representation of the atmosphere using a uniform model and data assimilation system (Gibson et al. 1996, 1997; Kalnay et al. 1996). Reanalysis winds and vorticity are more reliable than rainfall or OLR (Kalnay et al (1996), and they provide a longer record compared to satellite derived OLR, and are more spatially complete compared to observed rainfall. Using 850hPa relative vorticity, Annamalai et al. (1999) showed that both the ECMWF and NCEP/NCAR reanalyses had nearly identical dominant modes of intraseasonal variability, characterized by a northwest to southeast tilt and northward propagation. Additionally, these modes were linked to the active and break monsoon over India. Compared to the results of Annamalai et al. (1999), the afore-mentioned model results of Ferranti et al. (1997) and Martin (1999) exhibited intraseasonal patterns that were too zonal, with the transition from ocean to the continent being more regime-like rather than of a propagating nature.

Observational evidence for a common mode of intraseasonal and interannual variability was found by Sperber et al. (2000) and Goswami and Ajaya Mohan (2001). This mode, shown in Fig. 11.5c, is characterized by cyclonic anomalies at 850hPa over India and anticyclonic anomalies to the south over the Indian Ocean. It shows a strong link to all-India rainfall manifested as a systematic shift in the mean of the frequency distribution of the principal component time series when stratified between years of above-normal and below-normal all-India rainfall (Sperber et al. 2000). Unfortunately, a direct link of this mode to slowly varying boundary conditions, which could be the source of predictability, has remained elusive. Other modes in the 850hPa wind are associated with the northward propagation of the tropical convergence zone, with that associated with the onset of northward propagation being linked to the phase of the El Niño/Southern Oscillation (Sperber et al. 2000). While encouraging from the viewpoint of predictability, this boundary forced mode is not the dominant mode of intraseasonal variability, and thus the chaotic nature of the other components of the BSISV can obscure the boundary forced signal.

The ability of atmospheric general circulation models to simulate the dominant modes of BSISV in the 850hPa winds using hindcast experiments run with observed SST was evaluated by Sperber et al. (2001). While the models were largely successful at representing the observed patterns, seen in Fig. 11.5, they overemphasized the role of EOF-1, and unlike the observations, most models linked this mode to the boundary forcing. As a result the models were predisposed to incorrectly project the subseasonal variability onto the seasonal rainfall, thus poorly representing the interannual variability. Similar to Ferranti et al. (1997), Molteni et al. (2003) found zonally oriented anomalies to be common between interannual and intraseasonal time scales using a more comprehensive suite of hindcast experiments with a later version of the ECMWF model. Though the principal component of the dominant mode was not correlated with ENSO, it did exhibit 'multiple-regime behavior' related to the strength of zonal asymmetry in equatorial Pacific SST, a characteristic yet to be seen in observations. As in Sperber et al. (2001) they noted "significant discrepancies from observations in the partition of variance between modes with different regional characteristics."

Overall, models show some ability to represent the observed spatial patterns of the 850hPa intraseasonal wind field, and poorer ability to represent the northward and eastward propagating rainband associated with the 30-50 day BSISV. Numerous factors complicate dynamical seasonal predictability of the summer monsoon. These include, but are not limited to, (1) the inability of models to realistically partition the relative importance of the dominant modes, (2) the failure of models to link these modes to the boundary forcing as observed, and (3) the fact that the ENSO forced mode is not the dominant mode of variability.

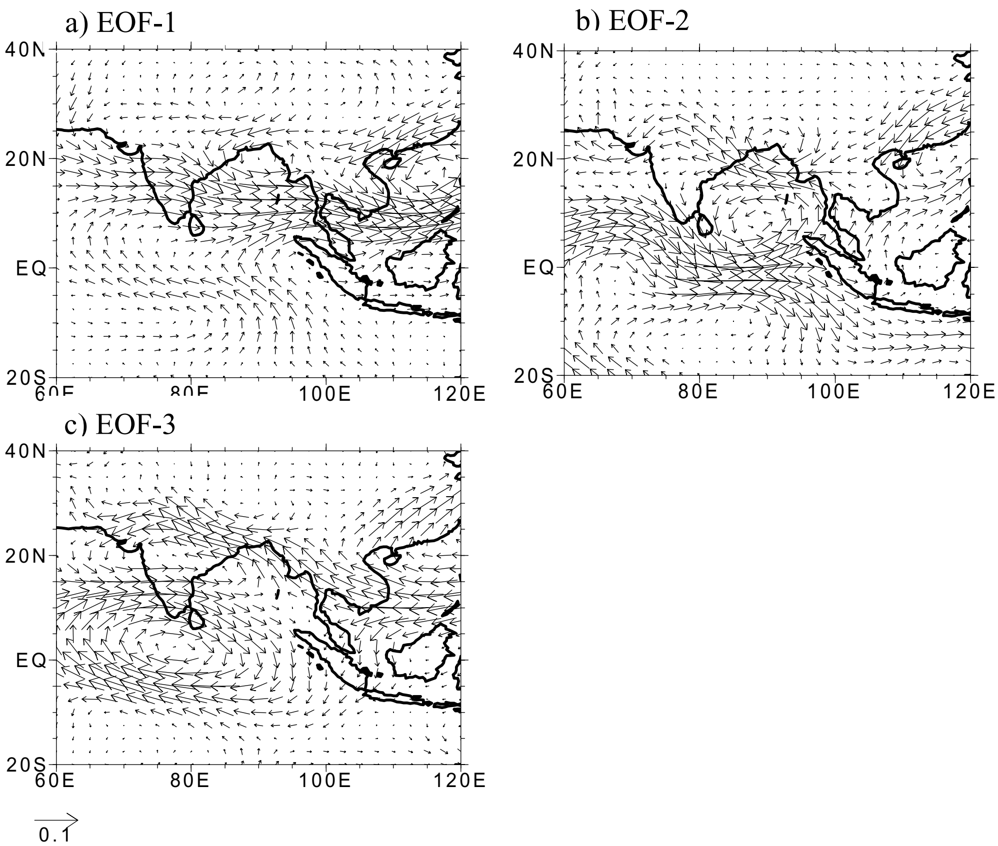

Figure 11.5: The dominant modes of boreal summer intraseasonal variability in the 850hPa winds from the NCEP/NCAR reanalysis (after Sperber et al. 2001).

The afore-mentioned results indicate that forecasting the statistics of boreal summer intraseasonal variability and its impact on the seasonal mean is a challenge that is limited by chaotic variability as well as model shortcomings. Despite this, there is another form of predictability that can be exploited because of the long time scale over which the BSISV evolves. The questions to be addressed include: (1) If BSISV is present, how far into the future can we predict its influence? (2) Is the degree of predictability dependent upon the strength and/or phase in the life-cycle from which the forecast is made? and (3) What aspects of the BSISV are most predictable? These are important questions to address since they can potentially influence crop selection and planting time as well as water resource management.

Such an investigation was undertaken by Waliser et al. (2003c) using the NASA Goddard Laboratory for Atmospheres atmospheric GCM, which has been used in a similar capacity to investigate potential predictability of the boreal winter MJO (Waliser et al. 2003d). Predictability was assessed based on the ratio of the deterministic intraseasonal signal from the control run to the mean-squared error from perturbed initial condition integrations. Overall, 200hPa velocity potential (rainfall) was predictable out to 25 (15) days, with the subset of strong intraseasonal cases having predictability extended by 10 (5) days compared to weak intraseasonal events. The suppressed phase exhibited a better signal to noise ratio at longer lead times compared to the convective phase. The results of this study are purely model generated, and thus are limited by the ability of the model to represent the BSISV. Other limitations include the use of climatological SSTs as the surface boundary condition, while as discussed earlier, air-sea interaction is important in the life-cycle of the MJO. Plans for experimental subseasonal forecasts have been outlined in a workshop summary (Waliser et al. 2003a), which also includes an assessment of model performance indicating that coupled models tend to more realistically represent the MJO than their uncoupled counterparts.

Modeling the BSISV has benefited from an understanding of the important role that air-sea interaction has played in representing the boreal winter MJO. Kemball-Cook et al. (2002) used the ECHAM4 model in coupled and uncoupled configurations. With air-sea feedback, space-time spectra of OLR showed a more realistic partitioning of variance between eastward and westward propagation near the equator. They also found that “coupling is helping to destabilize the northward moving mode by enhancing low-level convergence into the positive SST anomaly.” However, unlike the reanalysis, the shortwave surface heat flux was more important than the latent heat flux for forcing the SST anomalies that are in quadrature with the convection, and the model also overestimated the strength of the low-level convergence. Thus, the model appears to compensate for the weak latent heat flux anomalies, suggesting that the BSISV is arising for the wrong combination of interactions. Despite this, the indication is the net surface heat flux is important for generating realistic SST anomalies, which in turn are important for modulating the propagation of the BSISV. Kemball-Cook et al. (2002) also found that the failure to generate easterly wind shear in the late summer precluded the emanation of Rossby waves and prohibited the northwestward propagating mode. As in the boreal winter case, this attests to the importance of simulating a realistic basic state to properly capture intraseasonal variability. In cases where there is an eastward propagating equatorial convective component, Kelvin wave/Rossby wave interactions and air-sea interaction both promote the northward propagation of precipitation resulting in the tilted rainband.

Using the Meteorological Research Institute CGCM2, Rajendran et al. (2004) presented additional evidence that air-sea interaction results in a more realistic BSISV. Compared to the uncoupled integration, the coupled model had 50% more northward propagating events, and exhibited surface flux, convection, and SST feedbacks that resulted in a more realistic life-cycle of the BSISV. Thus it appears that air-sea interaction gives rise to a more accurate simulation of intraseasonal variability, provided the model has a realistic mean state. An important question for the future is: What are the relative contributions of the Kelvin wave/Rossby interactions versus the air-sea interaction for promoting the northward propagation? Fu et al. (2003) suggest that air-sea interaction is the most important process. They note cases of northward propagation that occur independently of an eastward equatorial propagating convective component, hence no contribution due to the Kelvin wave/Rossby wave interactions, in which the northward propagation occurs solely due to air-sea interaction. Conversely, numerous GCM studies discussed earlier in this subsection showed some ability to generate northward propagation using prescribed SST, suggesting that processes other than air-sea interaction are also important. What is needed is a better understanding of the hierarchy of subseasonal modes of monsoon variability (e.g., Wang and Rui 1990, Sperber et al. 2000), and the mechanisms that control them.

3. Concluding remarks

It is certainly true that the simulation of the MJO by general circulation models is improving, along with our understanding of what are the key processes for its initiation and maintenance. However, it is still not the case that a good representation of all aspects of the MJO is inherent in the majority of the current generation of GCMs. Recent research has pointed to possible avenues that might lead to improvements in the simulation of the MJO in the coming years. Firstly, greater emphasis is being placed on understanding the suppressed phase of the MJO and the processes that recharge the tropical troposphere for the next period of active convection. Steps are being taken to represent cumulus congestus clouds in convection schemes, including warm rain processes, which are key to the life cycle of these clouds.

Secondly, there is good evidence that the MJO in both boreal winter and summer manifestations is, at least to some extent, a coupled ocean-atmosphere mode. Whilst coupled models are capable of producing the correct relationship between convection and SST on intraseasonal timescales, these models still underestimate the activity of the MJO (e.g. Inness et al. 2003) and the magnitude of the SST perturbations is smaller than observed. This is despite variations in the surface fluxes that are similar to those observed. This suggests that the representation of the upper layers of the ocean may not be responding realistically to subseasonal variations in winds and fluxes.

Most coupled climate models have a relatively coarse vertical resolution in the upper ocean, typically of the order of 10 meters. But observations by tethered buoys, such as the Woods Hole IMET buoy during TOGA-COARE (e.g. Anderson et al. 1996), have shown that the upper ocean has a very complex structure, which undergoes dramatic changes during the lifecycle of the MJO. A particularly noteworthy aspect of these buoy observations is the diurnal variation in SST that only occurs during suppressed phases of the MJO, when the winds are light, the net heat flux into the ocean is large and the mixed layer is very shallow. In a study with a very high vertical resolution mixed layer model, Bernie et al. (2004) have shown that the rectification of these diurnal variations on to intraseasonal timescales is significant and accounts for a large proportion of the intraseasonal warming of the ocean during the suppressed phase of the MJO. Clearly, the coarse resolution of the upper ocean in current coupled models and the lack of resolution of the diurnal cycle in the coupling frequency means that these diurnal variations in SST and their rectification on to intraseasonal timescales are not represented. Bernie et al. (2004) concluded that a resolution of 1 meter for the skin layer of the ocean and a coupling frequency of at least every 3 hours are needed to adequately capture diurnal and intraseasonal SST variability. As Fig. 11.6 shows, only simulations with high frequency coupling and a shallow top layer are capable of reproducing the observed signal.

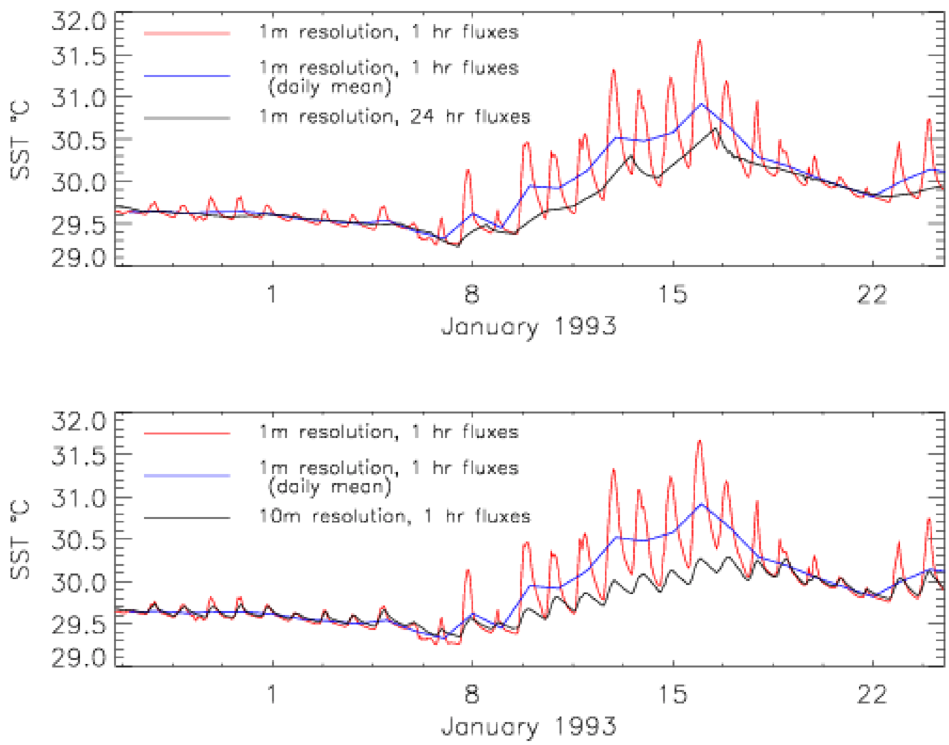

Figure 11.6: Impact of coupling frequency (upper panel) and resolution of uppermost ocean (lower panel) on simulations of the diurnal and intraseasonal variations in SST for TOGA-COARE with a mixed layer ocean model. The observed SSTs are very close to the red curves. From Bernie et al. (2004).

The diurnal SST variations may also be important for the MJO in other ways. Johnson et al. (1999) showed that cumulus congestus clouds are most prevalent during light wind conditions in the presence of a strong diurnal cycle in SST. These clouds occur most frequently in the late afternoon, with a behavior that resembles more closely the diurnal cycle in land convection, suggesting that they may be triggered by the diurnal cycle in SST. The fact that these clouds appear to be key players during the suppressed phase of the MJO adds further weight to the need for taking a complete atmosphere-upper ocean approach to simulating the MJO.

Although the focus of this chapter has been on modelling the MJO, other aspects of subseasonal tropical variability need to be considered. Interactions between multiple timescales of variability in the tropics have been the subject of several papers (e.g. Nakazawa 1988, Lau et al. 1991), suggesting that the synoptic scale, higher frequency modes of convective activity are modulated by the MJO. How much the synoptic and mesoscale activity embedded within the MJO is responsible for the evolution of the oscillation itself remains an open question (e.g. Hendon and Liebmann 1994). The importance of equatorial wave modes for organizing tropical convection in general has been highlighted by Wheeler and Kiladis (1999) and Yang et al. (2003). In fact, the results of Yang et al. (2003) suggest that the majority of tropical convection is associated with equatorial Kelvin, Rossby and mixed Rossby-gravity waves, which undergo Doppler shifting and changes in vertical structure depending on the basic state wind and vertical shear. Yang et al. (2003) also showed that the structure of the waves is substantially modified over the Indo-Pacific Warm Pool by equatorial convection induced through wind-evaporation feedbacks. However, a preliminary analysis of these waves in the AMIP II models (M. Wheeler, personal communication), in coupled models (AchutaRao et al. 2004), and in the Met Office UM (Yang et al. 2004) has shown major deficiencies in their structure and their coupling with convection. Since these waves are the building blocks of the tropical climate and are fundamental to the simulation of the MJO, future efforts to model the MJO must also address the more general issue of convectively coupled equatorial waves.

Finally, the measures used to determine the quality of the MJO simulation are very important. Early GCM studies of the MJO tended to concentrate on the signal in upper tropospheric tropical winds or velocity potential. It could be that *in situ* intraseasonal modulation of the main convective region over the Indo-Pacific warm pool produces an equatorially trapped Kelvin wave response, which resembles the MJO signal in the upper level winds, without actually being accompanied by an eastwards propagation of the main convective region through the Indian Ocean and into the west Pacific. The need to use a reasonable range of diagnostics to determine the quality of the MJO simulation is clearly important, in which the signal of the MJO in the upper tropospheric winds should be regarded as a bare minimum indication of the presence of the MJO. The evolution of convection through the cycle of the MJO, with particular emphasis on the eastward propagation must be examined. Finally, the intraseasonal variability of surface fluxes and their impact on SST should be diagnosed, ensuring that the coupled nature of the simulated MJO is properly represented.

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