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Chapter 11: Modeling Intraseasonal variability

K. R. Sperber, J. M. Slingo, P. M. Inness

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Intraseasonal Variability in the Atmosphere-Ocean Climate System

CHAPTER 11:

MODELING INTRASEASONAL VARIABILITY

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11.1 INTRODUCTION

The Madden-Julian Oscillation (MJO) has long been an aspect of the global climate that has provided a challenging test for the climate modeling community. Since the 1980's there have been numerous studies of the simulation of the MJO and boreal summer intraseasonal variability (BSISV) in general circulation models (GCMs), ranging from Hayashi and Golder (1986, 1988) and Lau and Lau (1986), through to more recent studies such as Zhang et al. (2006), Sperber and Annamalai (2008), and Kim et al. (2009). 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, the 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 (e.g. Swinbank et al. 1988), 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; Sperber et al. 1997; 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, following the more limited intercomparison of Park et al. (1990), 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?
- How does the intraseasonal oscillation depend on aspects of a model's basic climate?
- What seasonal and interannual variability in the activity of the MJO is simulated? How does it compare with reality?

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, 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 the study of Slingo et al. (1996), Sperber et al. (1997) focused on the most skilful models in AMIP I, and 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.

More recent intercomparisons have shown that most models are still unable to reproduce the observed concentration of power at the 40-50 day timescale with the precipitation signal being too weak in most models (Wu et al. 2002; Lin et al. 2006, 2008; Zhang et al. 2006; Kim et al. 2009). However, progress in simulating the MJO is being made. At a workshop on simulation and prediction of subseasonal variability in 2003 (Waliser et al. 2003c), most of the models presented were able to simulate at least some aspects of the MJO. 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. More recently, Sperber and Annamalai (2008) demonstrated that virtually all of the Coupled Model Intercomparison Project-3 (CMIP3) models produce eastward propagation of intraseasonal convective anomalies over the Indian Ocean, a demonstrative improvement compared to previous generations of models. 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 as 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 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.

11.2 MODELING THE MJO IN BOREAL WINTER

11.2.1 Interannual and decadal variability of the MJO

Slingo et al. (1996) introduced an index of MJO activity based on the near-equatorial zonal wind at 200hPa, to provide a preliminary measure of MJO variability in models and to describe the interannual and decadal variations in MJO activity (Figure 11.1). This index uses the fact that the MJO projects on to the zonal mean of the equatorial zonal wind component through its Kelvin and Rossby wave characteristics (Slingo et al. 1999).

This index also shows that there is substantial interannual variability in the activity of the MJO, which Slingo et al. (1999) and Hendon et al. (1999) found was not strongly related to sea surface temperatures (Figure 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. In a related study, Gualdi et al. (1999) also showed that the only with a very large ensemble was it possible to detect any predictability for the interannual behaviour of the MJO. These results 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; Kessler and Kleeman 2001; Lengaigne et al. 2004; see Chapter 6 herein).

Also evident in Figure 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 inadequate 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 Figure 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. Zveryaev (2002) also notes interdecadal changes in intraseasonal variability during the Asian Summer Monsoon. Slingo et al. (1999) based their results on the NCEP/NCAR Reanalyses. The fact that very similar results have been obtained from the ECMWF 40-year Reanalysis (ERA-40) as shown in Figure 11.1 adds credence to the decadal variability identified earlier.

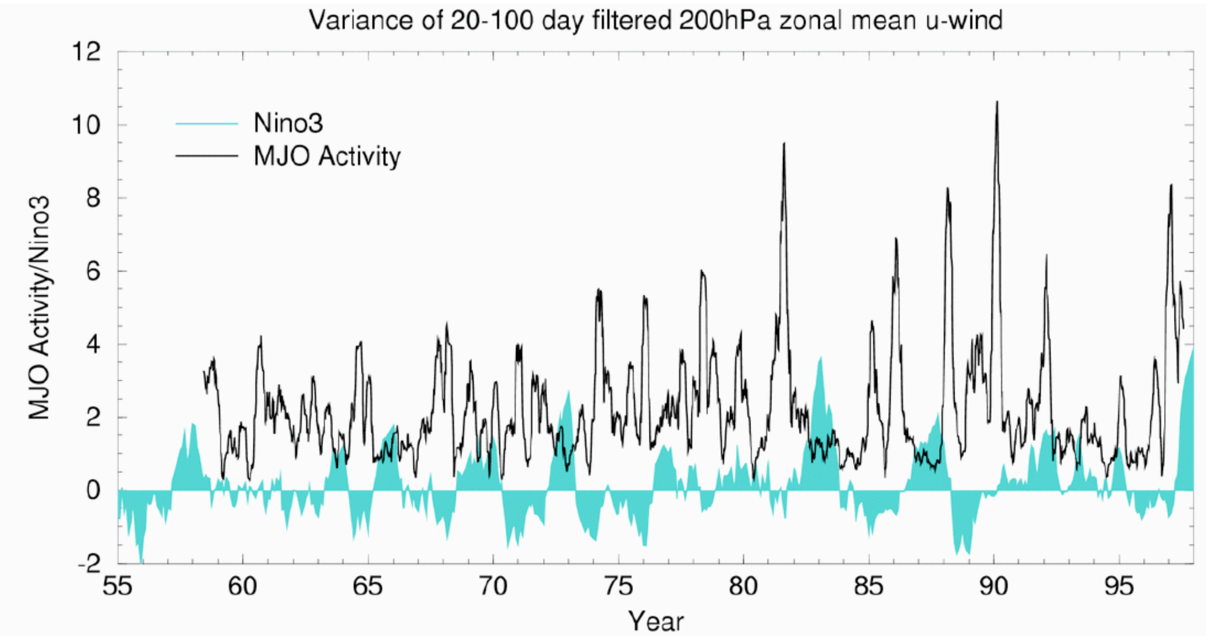

Figure 11.1: *Interannual variability in the activity of the MJO as depicted by the time series of the variance (m^2s^{-2}) of the 20-100 day band pass filtered zonal mean zonal wind from the recent ECMWF Reanalysis for 1958-97 (ERA-40). A 100-day running mean has been applied to the variance time series. The lower, shaded curve is the sea surface temperature anomaly (K) for the Niño3 region (5^oN-5^oS, 90^oW-150^oW). See Slingo et al. (1999) for more details on the calculation of the MJO index.*

11.2.2 Sensitivity to the formulation of the atmospheric model

In the 1980s, the resolution of GCMs was low (typically spectral T21, R15, equivalent to a grid of ~5^0) 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 (spectral T106, ~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 spectral 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, evidence from ECMWF suggests no improvement in the simulation of the MJO (Jung and Tompkins 2003). Rather, Bechtold et al. (2008) indicate that improvements to convection and diffusion are responsible for an improved representation of the MJO in the ECMWF Integrated Forecast System. Similarly, improved physics and dynamics in coarse resolution climate models has led to better fidelity in representing the MJO (e.g., Ringer et al. 2006), and importantly other GCMs that use convective parameterization have been able to produce credible simulations of the MJO (e.g., Kemball-Cook et al. 2002; Sperber et al. 2005; Sperber and Annamalai 2008; Sperber et al. 2008). 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 parameterization has been replaced by a 2-dimensional cloud-resolving model (CRM) – the "cloud-resolving convective parametrization" or super-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. Use of a CRM in this way provides useful insights into fundamental aspects of organized convection in the tropics and how to address sub-gridscale processes. For example Thayer-Calder (2008) and Thayer-Calder and Randall (2009) have noted that the relationship between column moisture and precipitation intensity is similar to observations in the super-parameterized Community Atmospheric Model (SPCAM), which has a realistic simulation of the MJO (Benedict and Randall 2009; Kim e al. 2009). However, this relationship was poorly represented in models that had problematic MJO simulations (Kim et al. 2009). Similar benefits are obtained by explicitly resolving cloud systems in ultra-high resolution global model simulations/hindcasts of the MJO (Miura et al. 2007; Miura et al. 2009) with Masunaga et al. (2008) gaining insight into shortcomings in the models parametrized cloud microphysics by comparing with Tropical Rainfall Measuring Mission (TRMM) and CloudSat observations. The ultra-high resolution approach also provides insight into multi-scale interactions that are embedded in the MJO, which are not otherwise resolved in coarse resolution GCMs (Oouchi et al. 2009), including MJO conditions under which generation of tropical cyclones is favourable (Taniguchi et al. 2010).

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; Figure 11.2).

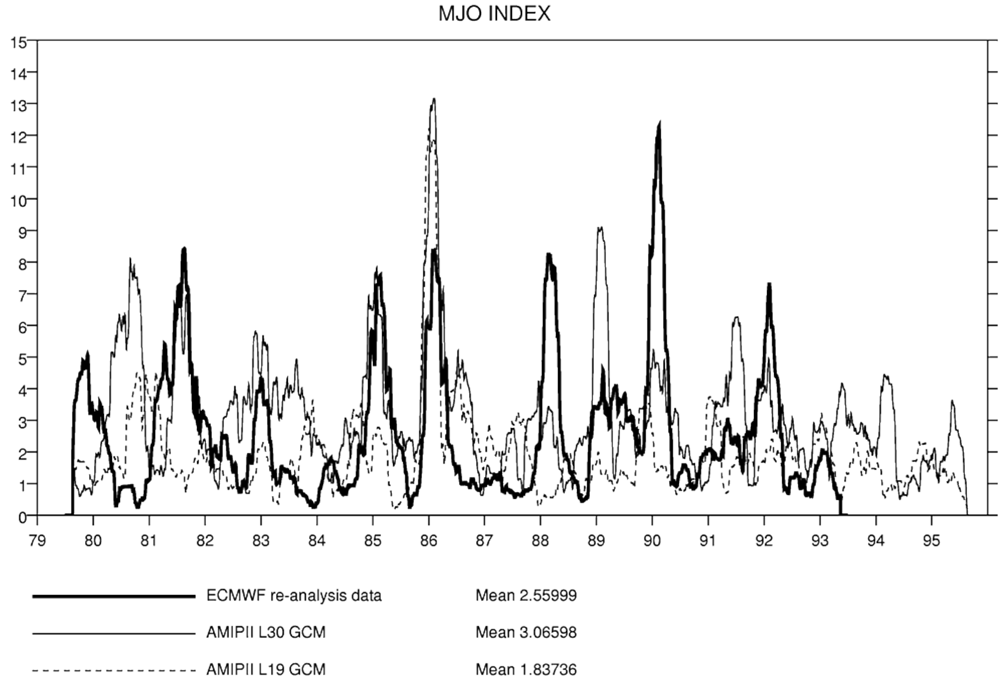

Figure 11.2: Influence of changing the vertical resolution in the Hadley Centre's atmospheric model (HadAM3) on the strength of the MJO as described by the index used in Figure 11.1. Note the increased amplitude of MJO activity in the L30 version of the model and the improved seasonality with respect the ECMWF Reanalyses. From 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 the 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 since observations indicate that shallow and cumulus congestus cloud dominate during the early-stage development of the MJO (Morita et al. 2006, Benedict and Randall 2007). 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. In the absence of resolving the tri-model distribution of clouds and the contribution of low-level clouds in moistening the atmosphere ahead of the deep MJO convection, models can compensate by exacerbating other interactions, such as lower tropospheric moistening due to reduced eddy moisture advection between the equator and poleward latitudes (Maloney 2009).

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. For example, 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.

Subsequently, 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. 2003c). 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 those of Maloney and Hartmann (2001) and Lee et al. (2003) have also demonstrated that considerable changes 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.

Many schemes use an equilibrium approach to convection, which assumes that instabilities are removed completely at each time step. 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, Salby et al. (1994) 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 frictional wave-CISK (see Chapter 10), 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 reinforces 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. The most skilful models in AMIP I did not employ frictional wave CISK or wind induced surface heat exchange (WISHE; Emanuel, 1987) for maintaining the MJO (Sperber et al. 1997). On the other hand, Waliser et al. (1999) noted that when coupling between the atmosphere and ocean was introduced (see Section 11.2.3), then frictional wave-CISK was enhanced and became an important factor in the improved simulation of the MJO.

With the low-level moisture convergence leading the convection, as suggested by Salby et al. (1994), then 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. More recent GCMs represent this process and these vertical structures as part of the mechanism for MJO propagation (Sperber et al. 2005; Benedict and Randall 2009). 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 (see Section 11.5).

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 atmospheric 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 superparametrization approach discussed earlier in this chapter (e.g. Grabowski and Moncrieff, 2002), with initial results indicating that the interaction of the clouds and radiation does indeed have a part to play in the large-scale organization of convection.

Tropical channel atmospheric models have also provided insight into mechanisms by which the MJO can be initiated. In these models, boundary conditions are specified at predetermined latitudes in the northern and southern hemisphere, while equatorward the system is free to develop on its own at all longitudes. Using the tropical channel version of the National Center for Atmospheric Research Mesoscale Model, Ray et al. (2009) found that extratropical disturbances from the Southern Hemisphere that propagate into the western Indian Ocean were the most important influence for initiating observed MJO's. The results were robust at lead times of >30 days, suggesting the potential for long-lead forecasts of the MJO beyond that estimated from perfect predictability experiments (Waliser et al. 2003b; see Chapter 12). Although latent heating and moist processes play an important role in the eastward propagation of the MJO, these processes were not found to be important in the initiation phase. Similarly, specification of time varying SST had no impact on the initiation of the MJO, though coupled air-sea interactions, which might amplify a local perturbation, were not considered by Ray et al. (2009). This suggestion of an extratropical trigger is consistent with the observed result of Matthews (2008), though in both studies the trigger was related to perturbations arising from an immediate predecessor MJO event but was not influential in initiating primary (spontaneously generated) MJO events.

11.2.3 Modeling the MJO as a coupled ocean-atmosphere phenomenon

One of the biggest advances in modeling the MJO has been in the recognition that it almost certainly involves coupling with the ocean, as discussed in Chapter 7 and references cited therein. 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 (Figure 11.3). As shown in Figure 11.3, 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, Figure 11.3 also shows the phasing of the surface flux and wind stress anomalies relative to the convective maximum.

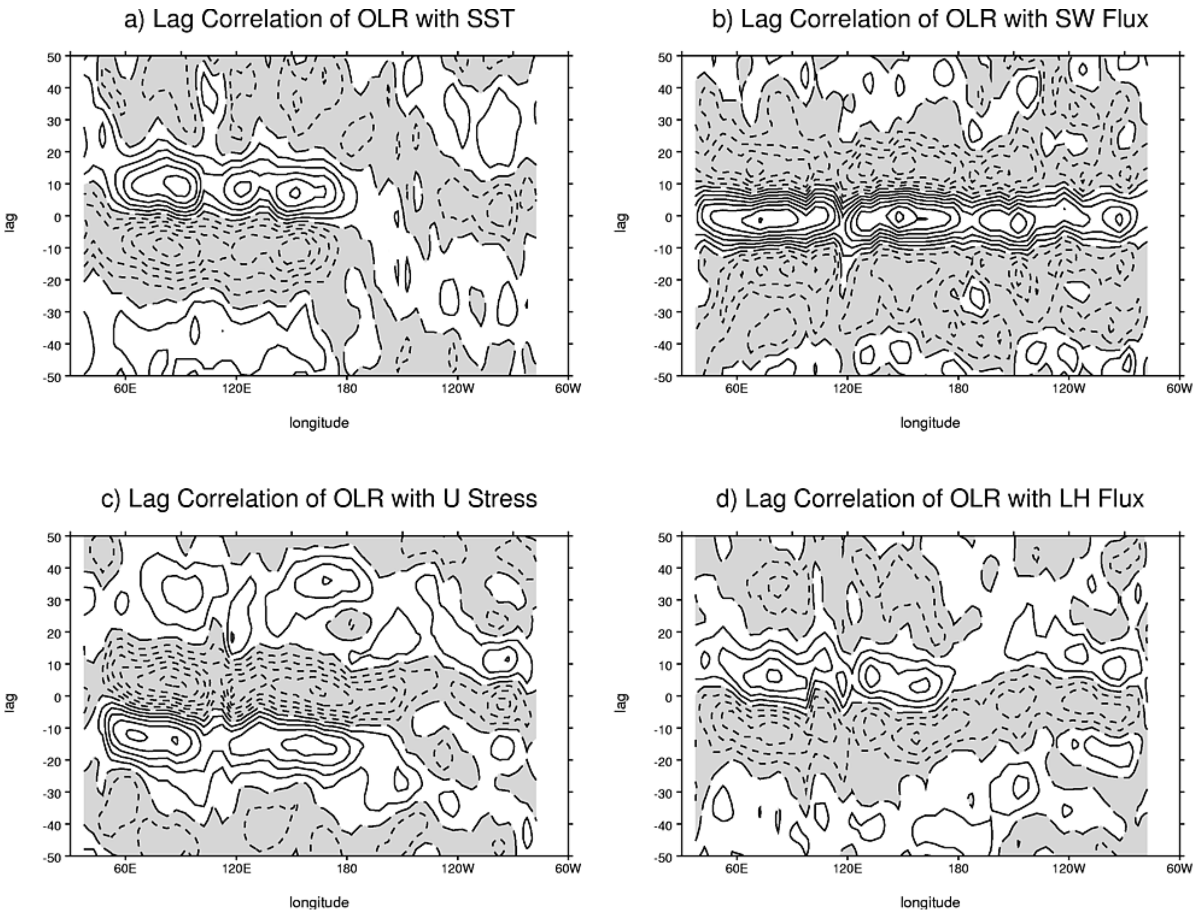

***Figure 11.3**: Lag correlations between observed outgoing longwave radiation (OLR; convection) and surface fields: (a) sea surface temperature (SST), (b) shortwave radiation, (c) zonal wind stress and (d) latent heat flux. Negative lags indicate that the convection lags the surface field, positive 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 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 modeling 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 $(50\ \text{days})^{-1}$. 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. Until ~2005, with the availability of the CMIP3 database, there were only a limited number of studies of the MJO in coupled GCMs in the literature. This arose since until quite recently the cost of running coupled GCMs was 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 had 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 of the coupled system might compromise the simulation of intraseasonal variability.

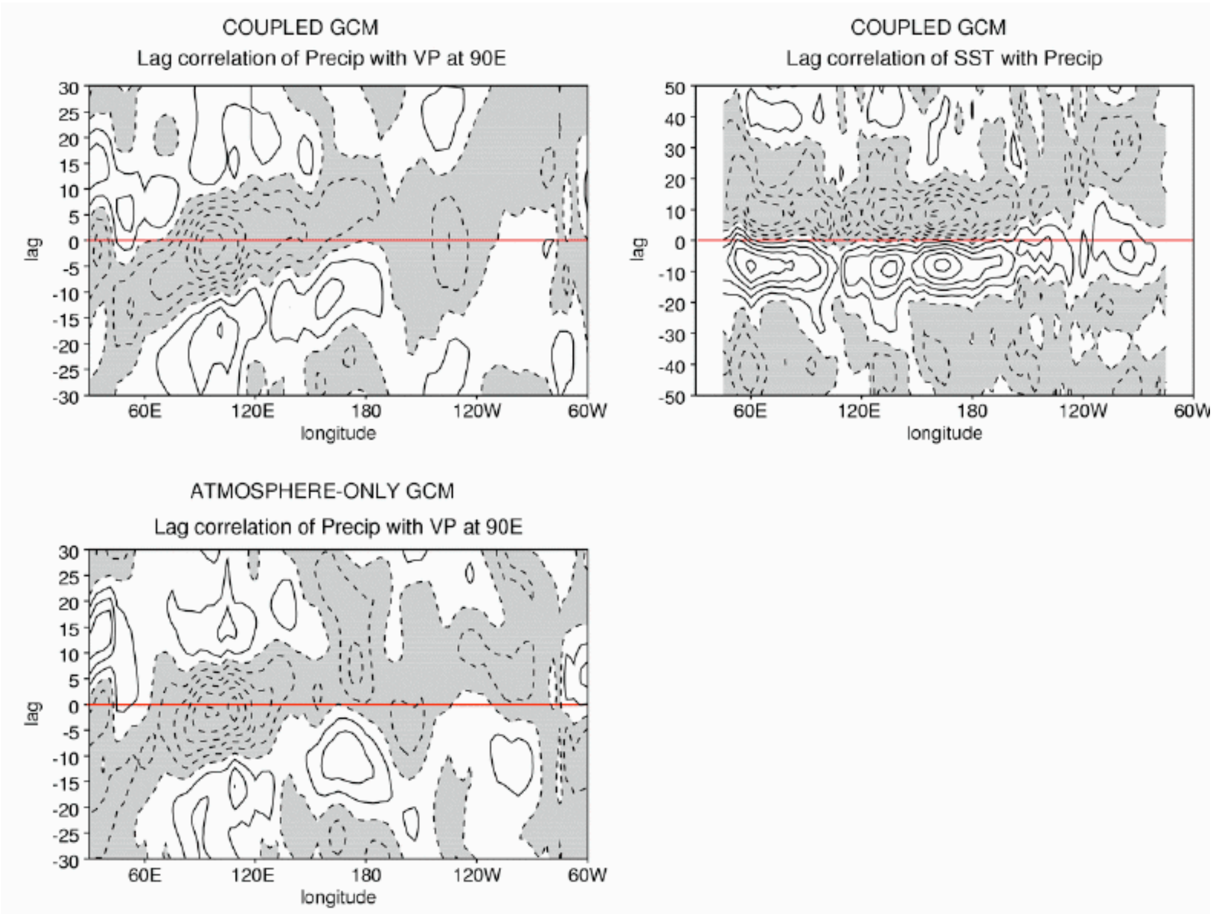

Figure 11.4: *Lag correlations between precipitation at every longitude and an index of MJO activity at 90°E, based on the 20-100day filtered 200hPa velocity potential, from (a) a version of the coupled ocean-atmosphere model, HadCM3, and (b) the equivalent atmosphere-only model, HadAM3. (c) shows the simulated lag correlations between the precipitation and SST at every longitude (as in Figure 11.3a) from HadCM3. From Slingo et al. (2003).*

Initial studies by Gualdi et al. (1999) and Hendon (2000) using fully coupled models concluded that an interactive ocean did not improve the MJO 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, Kemball-Cook et al. (2002), Inness and Slingo (2003), Inness et al. (2003), and Sperber et al. (2005) 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 (Figure 11.4). Whereas the atmosphere-only model had a predominantly standing oscillation in the convection (Fig 11.4b), the coupled model produced a more realistic eastward propagating signal (Fig 11.4a). This was associated with coherent variations in SST (Figure 11.4c), which showed a similar phase relationship with convection as in observations, with warmer SSTs preceding the maximum in convection by 5-10 days.

Due to the increased number of degrees of freedom in a fully coupled 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.

11.3 BOREAL SUMMER INTRASEASONAL VARIABILITY

As noted in the Introduction (Section 11.1), the MJO during boreal summer is much more complex, and the eastward propagation is often accompanied by northward propagation over the Indian Ocean sector. A brief discussion of boreal summer intraseasonal variability (BSISV) follows in order to characterize the basic challenges to the modeling community. A more comprehensive discussion of observed variability is presented in Chapters 2 and 3. The BSISV is important because it is intimately related to the active/break cycles of the Asian summer monsoon (Krishnamurti and Bhalme 1976; Sikka 1980; Gadgil and Asha 1992; Webster et al. 1998; Annamalai and Sperber 2005). 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 11.5a shows the composite OLR from observations corresponding to active convection/rainfall over India, extending to the southeast into the western Pacific. As this tilted rainband propagates to the east, rainfall occurs further north at about 1^{o} latitude per day 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 10. 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 (2005) 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). The importance of forced Rossby waves for the tilted rainband was also highlighted in a full GCM by Wu et al. (2006). Annamalai and Sperber (2005) also concluded that the intraseasonal variability over the Indian Ocean and the West Pacific are mutually dependent systems. That is, the eastward extension of the equatorial convection over the eastern Indian Ocean is important for setting up the tilted rainband, while the subsequent convection over the West Pacific helps initiate the monsoon break over India, and the Indian Ocean convection can modulate the active and break phase over the West Pacific.

As during boreal winter, low-level moisture convergence is important for maintaining the eastward propagation of near-equatorial convection 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.

11.3.1 GCM simulations

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.

As with the boreal winter MJO, studies of the sensitivity of BSISV to horizontal resolution have been inconclusive. Using the Geophysical Fluid Dynamics Laboratory GCM, Hayashi and Golder (1986) found that R30 ($\sim 3^{o}$) represented better the space-time spectra of rainfall compared to the R15 ($\sim 5^{o}$) 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 ($\sim 5^{o}$) 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 a resolution of T106 ($\sim 1^{o}$) was needed to represent the northward propagation of the tropical convergence zone and the sudden jump of the Mei-yu front over China, although later work has suggested coarser resolution models with may have similar capabilities (Lau and Yang, 1996, Martin, 1999). In fact the differences among models are mainly associated with the combinations of, improvement in, and the addition of physical parameterizations.

The ability of models to simulate the dominant BSISV convective pattern has remained problematic, as shown in Figure 11.5. This result, from CMIP3 study by Sperber and Annamalai (2008), demonstrated that only two models (Figs. 11.5h-i, ECHAM4/OPYC and ECHO-G) represent the tilted convection that extends from India to the Maritime Continent. While many of the CMIP3 models exhibited northward propagation of intraseasonal convective anomalies (Lin et al. 2008), Sperber and Annamalai (2008) showed that only the two afore-mentioned models simulated the northward propagation that is observed to occur in conjunction with the eastward propagation of near-equatorial convection (Annamalai and Sperber 2005); that is, properly generating the tilted rainband due to the forced Rossby wave response described in Section 11.3. Despite this limited success at capturing the off-equatorial convective signal, all of the CMIP3 models simulated eastward propagation of intraseasonal equatorial convective anomalies over the Indian Ocean (Sperber and Annamalai 2008). This is a demonstrable improvement compared to the older models analyzed by Waliser et al. (2003a), in which none of the models exhibited any systematic intraseasonal rainfall variability over the Indian Ocean.

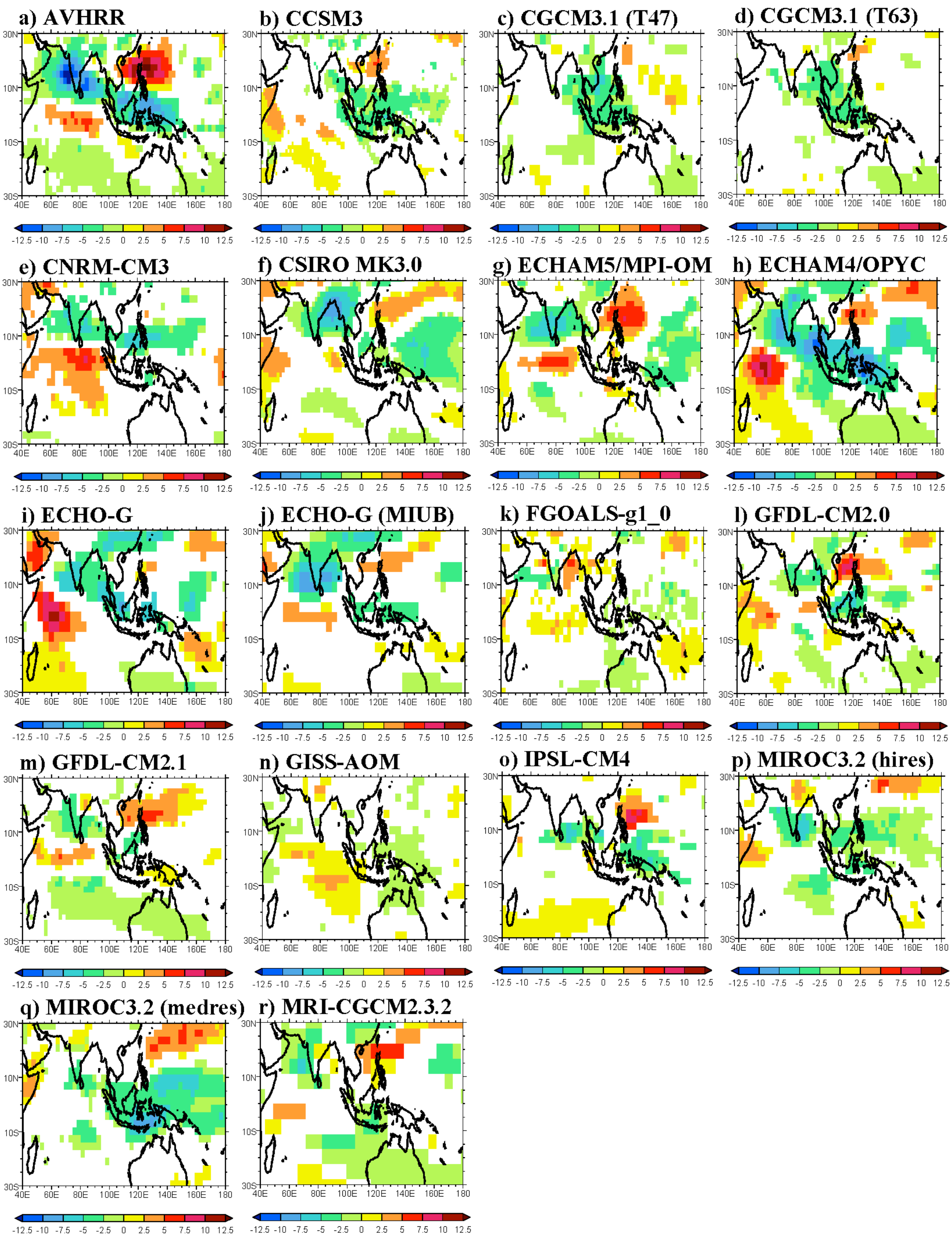

Figure 11.5: *Simulated BSISV convective anomalies relative to the observed day10 pattern. (a) observations (AVHRR outgoing longwave radiation), (b) CCSM3, (c) CGCM3.1 (T47), (d) CGCM3.1 (T63), (e) CNRM-CM3, (f) CSIRO MK3.0, (g) ECHAM5/MPI-OM, (h) ECHAM4/OPYC, (i) ECHO-G, (j) ECHO-G (MIUB), (k) FGOALS-g1_0, (l) GFDL-CM2.0, (m) GFDL-CM2.1, (n) GISS-AOM, (o) IPSL-CM4, (p) MIROC3.2(hires), (q) MIROC3.2 (medres), and (r) MRI0CGCM2.3.2. After Sperber and Annamalai (2008).*

11.3.2 Air-sea interaction and boreal summer intraseasonal variability

Observations indicate that systematic SST changes over the Bay of Bengal occur in conjunction with the northward propagation of intraseasonal convection (Vecchi and Harrison, 2002). The tendency is for warm (cold) anomalies to lead enhanced (suppressed) convection, suggesting that air-sea interaction may be important for northward propagation of the BSISV, in addition to the Kelvin wave/Rossby wave interactions discussed in Section 11.3. Modeling of BSISV has also benefited from an understanding of the important role that air-sea interaction has played in representing the boreal winter MJO. For example, using the ECHAM4 model in coupled and uncoupled configurations, Kemball-Cook et al. (2002) showed that with air-sea feedback the space-time spectra of OLR displayed 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 model shortwave surface heat flux was more important than the latent heat flux for forcing the SST anomalies that are in quadrature with the convection. In addition, 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 from the wrong combination of interactions. Despite this, the indication is that 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 the dynamics important for simulating intraseasonal variability. In cases where there is an eastward propagating equatorial convective component, Kelvin wave/Rossby wave interactions and air-sea interaction both promoted the northward propagation of precipitation resulting in the tilted rainband.

Further support that both dynamical processes and air-sea interaction are important for generating boreal summer northward propagation in climate models has been reported by Rajendran et al. (2004) and Rajendran and Kitoh (2006) using the Meteorological Research Institute CGCM2. The presence of northward propagation in the prescribed SST simulations indicted that dynamical processes play an important role for their development. However, the inclusion of air-sea feedback in the coupled model resulted in 50% more northward propagating events, and exhibited surface flux, convection, and SST feedbacks that resulted in a more realistic life cycle of the BSISV. Wang et al. (2009) also found an improved representation of the northward propagation in case study experiments with the National Centers for Environmental Prediction (NCEP) coupled atmosphere–ocean Climate Forecast System (CFS) compared to the NCEP Global Forecast System (GFS) in which the SST is prescribed. 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 (Inness et al. 2003, Seo et al. 2005). 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 such that the northward propagation occurs solely due to air-sea interaction rather than with a contribution from Kelvin wave/Rossby wave interactions. Conversely, numerous GCM studies have shown some ability to generate northward propagation using prescribed SST (e.g., Ajaymohan et al. 2010), suggesting that internal processes can also dominate. 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, including land surface processes that may affect the land-sea temperature gradient which could promote or diminish the northward propagation.

11.3.3 Modeling studies of the links between boreal summer intraseasonal and interannual variability

In the mid-1990's, modeling studies of BSISV 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 these 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 propagating. Furthermore, the first mode in the models explained far more of the sub-seasonal variance than in the observations.

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 Figure 11.6c, is characterized by cyclonic flow at 850hPa over India and an anticyclone 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 a source of predictability, has remained elusive. EOF's 1 and 2 in the 850hPa wind are associated with the northward propagation of the tropical convergence zone (Figures 11.6a and 11.6b), with EOF-2 being linked to the phase of the El Niño/Southern Oscillation (Sperber et al. 2000). While encouraging from the viewpoint of predictability, this is not the dominant mode of intraseasonal variability, and thus the chaotic nature of the other components of the BSISV can obscure a boundary forced signal.

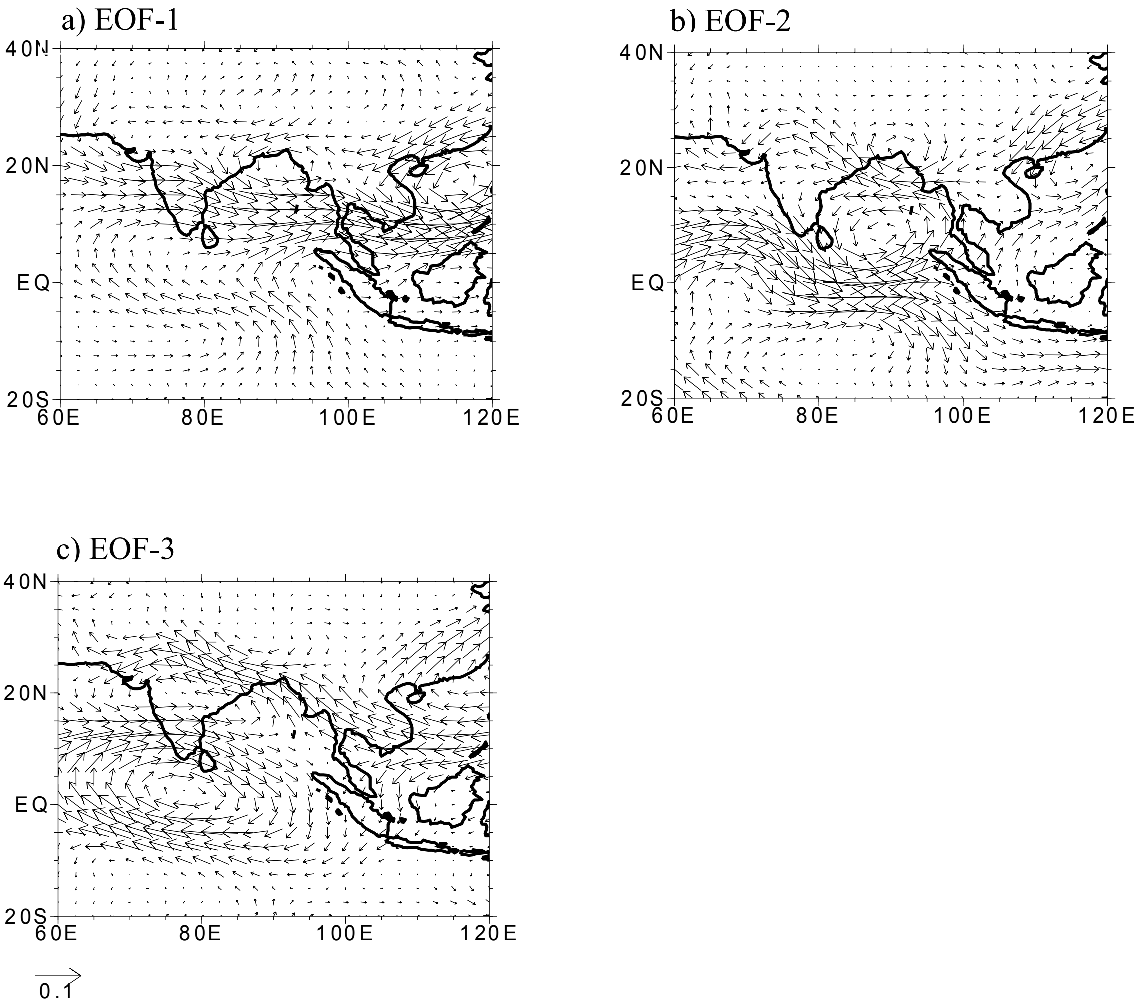

__Figure 11.6__: The dominant modes of boreal summer intraseasonal variability in the 850hPa winds from the NCEP/NCAR reanalysis. After Sperber et al. (2000).

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 Figure 11.6, 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, (i) the inability of models to realistically partition the relative importance of the dominant modes, (ii) the failure of models to link these modes to the boundary forcing as observed, and (iii) the fact that the ENSO forced mode is not the dominant mode of variability.

In the last several years modeling studies of the BSISV have become more frequent as we push our models to excel over a broader range of capabilities. Success in simulating the BSISV, with its poleward-propagating component, is an even more sensitive test of a GCM's capability than simulating the MJO, which is dominated by near-equatorial propagation. This partly arises because the simulation of the mean climate of the Asian Summer Monsoon continues to prove a challenge. Furthermore our basic understanding of what drives the BSISV and its northward versus eastward propagation is not so advanced, and we do not fully understand the role that land surface processes and the Tibetan Plateau may play in the evolution of the BSISV. Yet the social and economic benefits from extended range prediction of BSISV could be huge and thus makes this a major challenge for the modeling community in the coming years.

11.4 THE IMPACT OF VERTICAL RESOLUTION IN THE UPPER OCEAN

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 (Sections 11.2.3 and 11.3.2). 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; Lin et al. 2006, 2008) and the magnitude of the SST perturbations is smaller than observed. This occurs despite the variations in the surface fluxes being similar to those observed, and 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, Shinoda and Hendon (1998) and Bernie et al. (2005) 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. (2005, 2007) 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, leading to stronger and more coherent MJO's (Bernie et al. 2008). As Figure 11.7 shows, only simulations with high frequency coupling and a shallow top layer are capable of reproducing the observed signal.

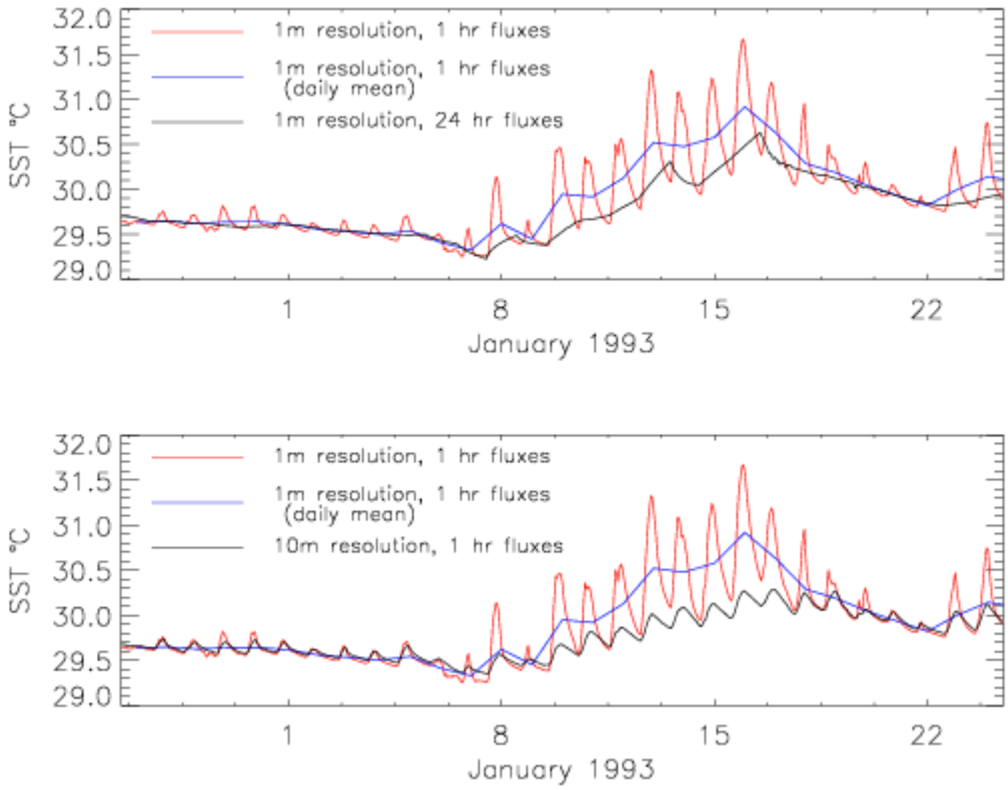

***Figure 11.7**: Impact of coupling frequency (upper panel) and resolution of uppermost ocean (lower panel) on simulations of the diurnal and intraseasonal variations in SST for TOGA-COARE with a mixed layer ocean model. The observed SSTs are very close to the red curves. From Bernie et al. (2005).*

The diurnal SST variations may also be important for the MJO in other ways. For example, 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.

11.5 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 recent CMIP3 GCMs. 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 improve the representation of cumulus congestus clouds in convection schemes, including warm rain processes, which are key to the life-cycle of these clouds.

Furthermore, 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). More generally, investigating the importance of equatorial wave modes for organizing tropical convection (Wheeler and Kiladis 1999, Yang et al. 2003) deserves more attention. 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, an analysis of these waves in the CMIP2 and CMIP2+ models (AchutaRao et al. 2004) and in the Hadley Centre's climate model (Ringer et al 2006) 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.

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 life cycle of the MJO, with particular emphasis on the eastward propagation, and in boreal summer also the northward propagation, must be further examined. Recent research has emphasized the complex 3-dimensional structure of the MJO, in particular the vertical distribution of the humidity field, and these should provide stringent tests for the model simulations (Sperber 2003; Kiladis et al. 2005; Tian et al. 2006; Thayer-Calder 2009). 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.

With these goals in mind, the limited-lifetime US CLIVAR MJO Working Group (MJOWG) was established in 2006 (Sperber and Waliser 2008). The MJOWG developed (1) a set of standard diagnostics to track progress in modeling the MJO (CLIVAR MJOWG 2009; Kim et al. 2009) with the latter authors also beginning to explore process-oriented diagnostics, and (2) initiated a World Climate Research Programme/Working Group on Numerical Experimentation (WCRP/WGNE) endorsed effort of making experimental operational MJO forecasts (Gottschalck et al. 2010). The Year of Tropical Convection MJO Task Force (YOTC MJOTF) is the follow-on group to the MJOWG, and is sponsored by the WCRP and the World Weather Research Programme (WWRP). The MJOTF is (1) developing process-oriented diagnostics, (2) developing boreal summer intraseasonal diagnostics and metrics, and (3) further developing MJO forecast techniques and (4) assessing impacts of the MJO on tropical cyclones and other phenomena.

Additional resources are currently being brought to bear in the investigation of the MJO, including the YOTC project (Waliser and Moncreiff 2008) which consists of a two-year period (May 2008-April 2010) "of coordinated observing, modeling, and forecasting of organized tropical convection." This effort will include numerous sources of high-resolution NWP analyses, exploit new satellite capabilities (e.g., CloudSat), and include numerical experimentation of case study periods "with the objective of advancing the characterization, diagnosis, modeling, parameterization and prediction of multi-scale convective/dynamic interactions," including the MJO/BSISV. Comparisons of coarse resolution and cloud system resolving GCMs in conjunction with observational process studies (e.g., Asian Monsoon Years [AMY], Matsumoto et al. 2008; the Cooperative Indian Ocean experiment on intraseasonal variability in the Year 2011 [CINDY2011], Yoneyama et al. 2009; Dynamics of the Madden-Julian Oscillation [DYNAMO], Zhang et al. 2010) will help foster improved parametrization for coarse resolution models, and expand our basic understanding and ability to model the MJO.

As our understanding of the MJO has increased, we are setting more stringent tests for our GCMs and NWP models in terms of what constitutes a 'good' MJO simulation, and we are testing experimental methods of forecasting the MJO/BSISV (see Chapter 12) due to its importance for medium-range and seasonal forecasts and the impact it has on the lives of those who live within the domain of its influence.

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