THE CMMAP MJO FOCUS THEME

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1. Introduction: Basic Issues and New Approaches[1]

Fundamental barriers to advancing weather and climate diagnosis and prediction on timescales from days to years are attributable to gaps in knowledge and the limited capability of contemporary operational and research numerical prediction systems to represent precipitating convection and its multi-scale organization, particularly in the tropics. In particular, the Madden-Julian Oscillation (MJO; Madden and Julian, 1972; Fig. 1) displays a multiplicity of interacting scales and strong three-dimensional transports of mass, momentum, and energy. The multi-scale organization of convection underscores a need to quantify the dynamical coherence, upscale evolution, and regime-dependent transport of organized systems and their representation in global models. Moreover, the effects of phase changes of water (the ultimate source of thermodynamic energy for deep convection) are manifested on various temporal scales: from convective-turnover and diurnal time scales (hours to a day), through the timescale of meso-convective organization (~days) to the residence time of water in the atmosphere (~2 weeks). Thus, the behavior and effect of water in the atmosphere in association with convective organization straddles the intersection of weather and sub-seasonal climate and has important implications for longer-term climate processes e.g., cloud-radiation interaction. The reader is referred to the review of Zhang (2006) for a more detailed background.

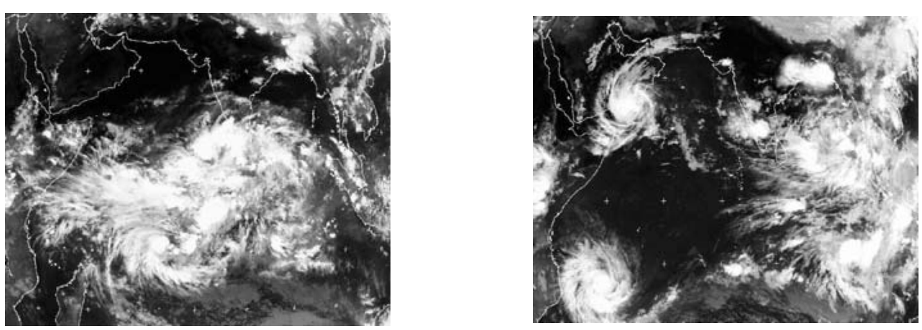

Figure 1: MJO convective organisation. An active MJO over the Indian Ocean on 2 May 2002 (left panel). A week later the MJO has moved eastwards over Indonesia, spawning two tropical cyclones in its wake (right panel). The multi-scale organisation of convection is clearly visible within the envelope of the MJO. The twin cyclones demonstrate graphically how high-impact organised weather events are associated by large-scale convective organisation and equatorial waves (Courtesy: Julia Slingo).

[1] For the most part, this section is extracted from a manuscript: “Organized Tropical Convection and Multiscale Interaction with the Global Circulation: A THORPEX and WCRP Collaborative Research Opportunity” by M. W. Moncrieff, M.A. Shapiro, J.M Slingo, and F. Molteni.

The MJO is increasingly recognised as influencing high-impact weather events and climate variability. It is also important in the socio-economic sense and across temporal scales. For example, the MJO is associated with: i) tropical cyclones, which are particularly severe weather events as poingantly illustrated in Fig.1; ii) tropical variability on sub-seasonal timescales such as breaks in the Asian, Australian and African monsoons which has imporant implications for life, agriculture, and infrastructure across the deep tropics; iv) global influences on through tropical-extratropical interactions and subsequent effects on the storm track in midlatitudes; v) a possible influence on interannual variability through affecting the genesis of El Nino. The reader is referred to Shapiro and Thorpe (2004) for more discussion of the effects of the MJO onhigh-impact weather events in midlatitudes. Yet, adequate knowledge of the processes contributing to the initiation and maintenance of the MJO and realistic simulations and predictions of the MJO, remain major scientific challenges to the weather/climate community.

1.1 Multi-scale convective organisation

A long-standing shortcoming of weather forecast and climate-prediction systems is their inadequate representation of subgridscale precipitation physics (Lin *et al.* 2006). The multi-scale organisation of precipitating convection and its interaction with the resolved-scale circulations is gaining prominence in the global modeling community. The issues are basic since the MJO is usually significantly different in coupled atmosphere-ocean models compared to atmosphere-only models. While there are reasons for such disparity, incomplete formulations of how boundary layers of the ocean and atmosphere interact are important issues, especially regarding the role of the MJO in the genesis of El Niño. Convective systems strongly affect surface radiative balance, evaporation, and wind stress which are key to atmosphere-ocean interaction.

Tropical convection organises on a remarkably wide range of spatial and temporal scales: i) cumulonimbus (~1- 10 km, hour); ii) meso-convective clusters (~100-500 km, day); iii) synoptic-scale superclusters (~1000-3000 km, week); iv) the MJO (~10000 km, weeks-months). A crucial unknown is how these multiple scales interact to form self-reinforcing, multi-scale organised systems. It is recognised that synoptic-meso-convective activity in the tropics is often coupled to preferred meriodinally-trapped modes of atmospheric variability described, to a first approximation, as Rossby-gravity waves and Kelvin waves.

Issues have been raised regarding: i) how convective activity is modulated by wave modes; ii) the degree to which convection forces atmospheric waves and *vice versa*; iii) feedback between convection and synoptic-scale to planetary-scale processes; iv) the upscale effects of meso-convective organisation (e.g., *via* thermodynamic and momentum transport) on large-scale atmospheric circulation; v) the effects of higher-latitude disturbances propagating into equatorial regions (e.g., cold surges originating in Siberia) on MJO genesis.

a) MJOs in parameterized global models

Figure 2 illustrates that MJOs in operational weather prediction disintegrates from the robust system in the analysis to a nonentity in a matter of days. Idealised global models (e.g., aquaplanet models) experience similar difficulty with the MJO, suggesting that the problem is fundamental.

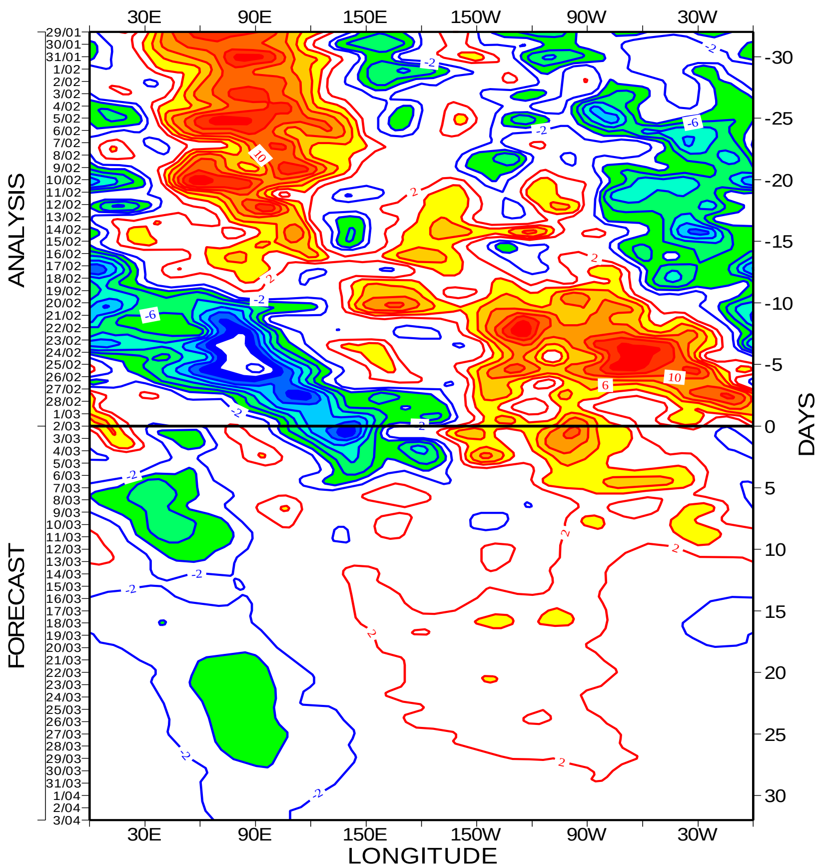

Figure 2: MJO within the ECMWF forecast system for an event in February 2006. The eastward propagating MJO is visible in the velocity potential (large-scale divergence) at 200hPa in the analyses, but the signal is lost rapidly within the forecast after 5 days (Courtesy: Adrian Tompkins, ECMWF).

Figure 3 illustrates the minimal consistency in MJO convective organisation among aqua-planet climate models applying different convective parameterisations; some systems propagate eastward, others westward; most likely, none of these realizations is truly a MJO. Another fundamental problem is the disparate spatial and temporal scales of the simulated convective organization.

b) Explicit representation of cloud-systems in global models

The explicit representation of precipitating convection by cloud-system resolving models (CRMs) is shedding new light on convective organisation, since the meso-convective organisation therein is more realistic than in contemporary parameterised global models. This class of modeling provides the prospect for improved representation of the MJO in weather/climate models. The global CRM is the state-of-the-art in explicit representation of multi-scale organization.

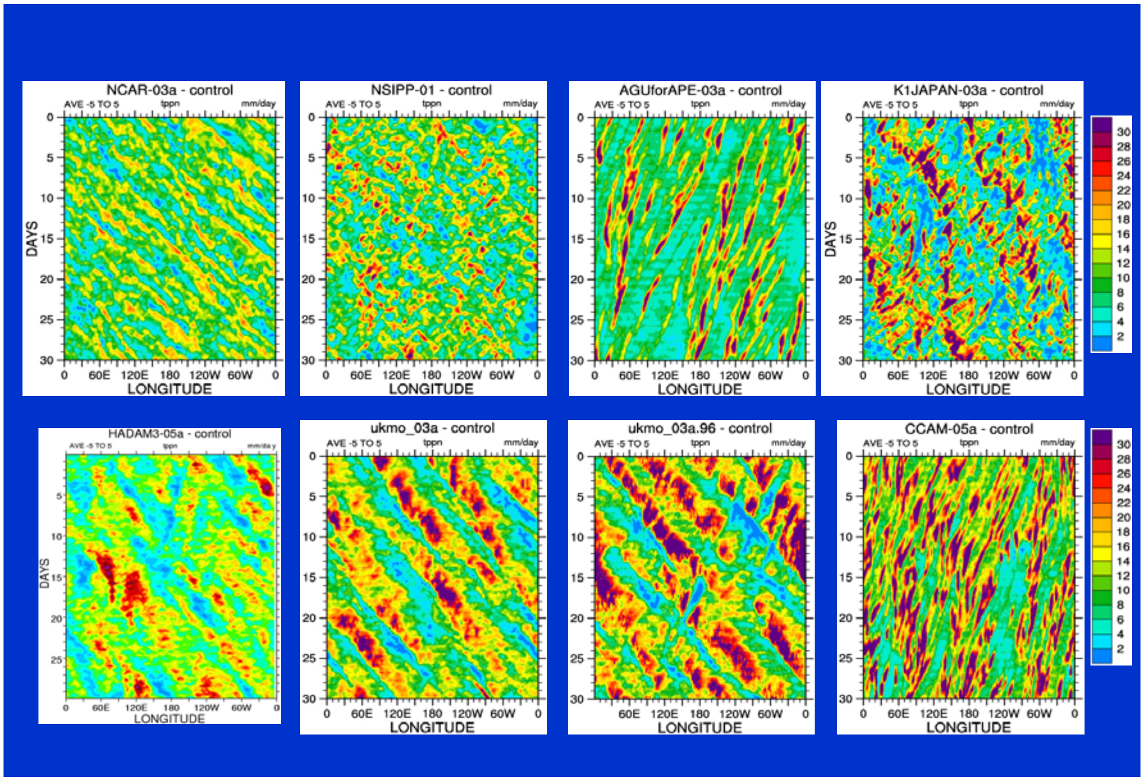

Figure 3: Large-scale organisation of tropical convection (precipitation) in climate models occurring some of the models participating in the Aqua-Planet Model Inter-comparison Project (http://www-pcmdi.llnl.gov/projects/amip/ape/). (Courtesy: Mike Blackburn, University of Reading, and Dave Williamson, NCAR.)

Figure 4 shows equatorial large/meso-convective organisation in a global CRM. Evident in this diagram are the eastward-propagating convective envelope and the embedded westward-propagating cloud clusters, resembling the multiscale organisation in nature e.g., Nakazawa (1988). Interestingly, MJOs occurring in global CRMs are usually too intense and persistent -- exactly the opposite from parameterised models. This behavior poses a new set of problems, arguably more amenable to solution than problems associated with contemporary parameterisation.

The explicit representation of convective organization is the basis of the superparameterisation approach: CRMs are applied in place of contemporary convective parameterisation. Superparameterisation was originally applied in the aquaplanet model of Grabowski (2001) and recently applied in full climate models (e.g., Khairoutdinov and Randall 2006).

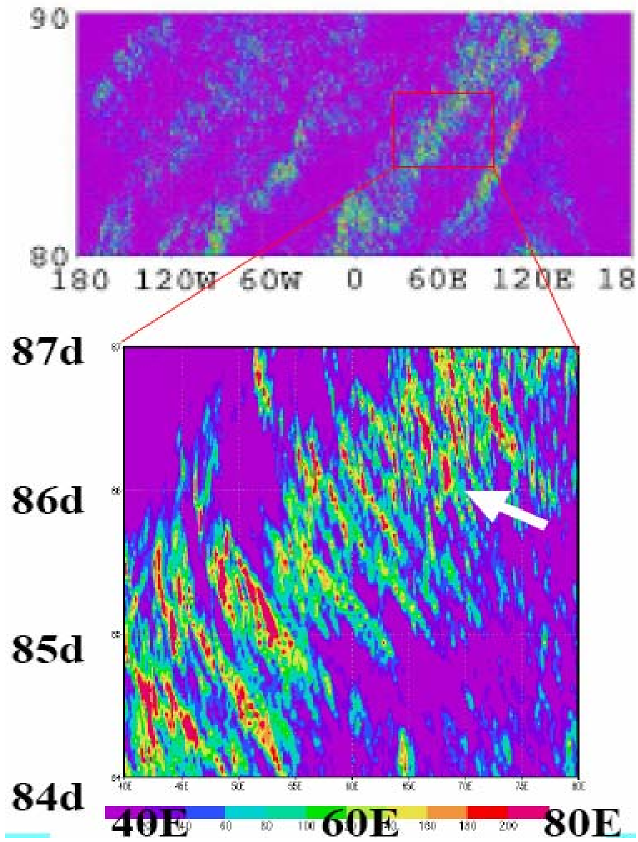

Figure 4: Simulated multiscale convective organisation in a global aquaplanet CRM at 3.5 km grid-spacing. Top, eastward-traveling convective envelopes and, bottom, a blow-up of the westward-traveling mesoscale convective systems (e.g., white arrow) in the top plate. (Courtesy: Satoh, Frontier Research Center for Global Change, Yokohama, Japan).

c) Dynamical models of multi-scale convective organization

The problem of quantifying the multi-scale organisation of precipitating convection and its interaction with the global circulation is unlikely to be solved through enhanced-resolution numerical simulations alone. Idealised models are useful for quantifying important issues, such as upscale transport associated with meso-convective organisation and mechanisms at work in numerically simulated multiscale systems. For example, the nonlinear mechanistic dynamical model of Moncrieff (2004) interlocks meso-convective organisation with Rossby-gyre dynamics and represents the morphology and upscale momentum transport properties. This model also simulates the vertical and meriodional transport and super-rotation properties of MJO-like systems generated by superparameterisation in Grabowski (2001). The quasi-linear multi-scale model of Biello *et al.* (2006), based on the systematic asymptotic perturbation theory of Majda and Klein (2003), shows that MJO-like systems can be intiated and maintained by organised upscale momentum and heat fluxes. Three categories of heating are represented: deep convection, stratiform, and congestus. Figure 5 illustrates: i) westward-tilted meso-synoptic eddies; iii) vertically and horizontally coupled cyclonic and anticyclonic gyres;

iii) a westerly-wind burst in the lower troposphere. These are the characteristic signatures of observed MJOs, giving plausible support for the hypotheses that MJO systems can be generated by upscale momentum transport in the vertical and horizontal.

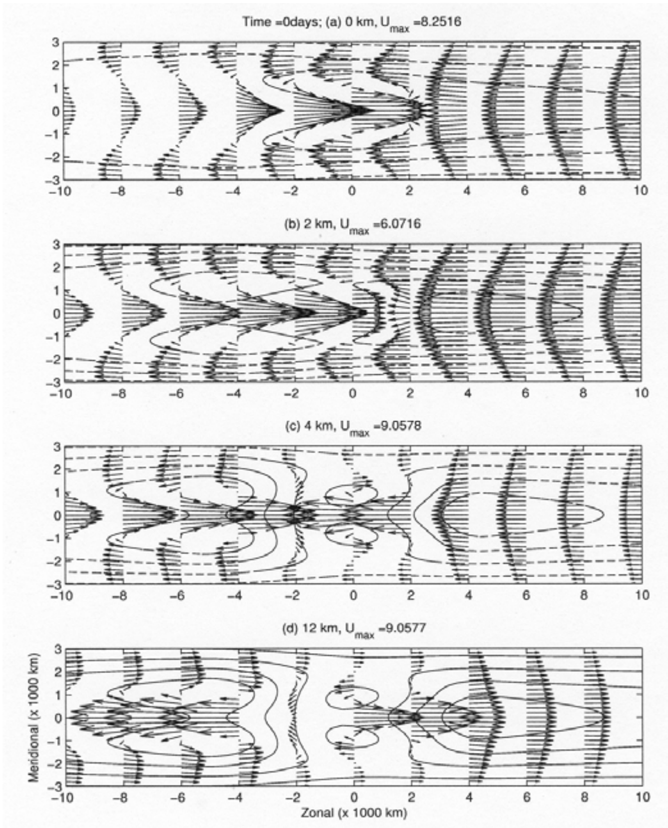

Figure 5: Horizontal velocity at selected heights in the troposphere, along with contours of the perturbation pressure in a multi-scale dynamical model forced by vertical fluxes of synoptic-scale heating and zonal momentum. Courtesy: Biello, Majda and Moncrieff (2007).

Another approach to idealised simulation of the MJO incorporates a dynamically active troposphere, a passive planetary boundary layer, and simple parameterisations of deep convection, surface heat exchange, and radiative cooling. This analog has crude vertical resolution, typically one or two baroclinic vertical modes described by $\sin(\pi z)$ and $\sin(2\pi z)$, respectively. Multi-scale convective organisation does occur in the first-baroclinic or 'shallow-water' versions of these models (Yano *et al.* 1995). However, the second-baroclinic mode results in more realistic MJO-like organisation (Khouider and Majda, 2006). This quantifies the importance of upper-tropospheric stratiform heating behind and low-to-mid tropospheric cumulus congestus heating in front of such systems, in agreement with the observed "tri-modal" characteristics of tropical convection; Johnson *et al*. (1999).

An important requirement for advancing the predictive skill of global weather/climate models is to derive parameterisations to allow the proper development of convective organization. This is a necessary requirement, since: i) convective organization is not realistically captured by present convective parameterisations; ii) the explicit approach to convection is too computationally intensive for inclusion in contemporary climate models. Idealised models quantify properties of multi-scale convective organization, e.g., vertical structure, transports, and propagation, and are therefore testbeds for the development of organized convection parameterisations.

2. MJOs in the CMMAP MMF

Realizations of the MJO in the CMMAP MMF provides an excellent opportunity to: i) evaluate the role of multi-scale organized convection in the genesis and maintenance of the the MJO; ii) improve the representation of MJOs in superparameterized models; iii) develop parameterizations of the MJO in coarse resolution climate models used in long simulations (e.g., IPCC assessments) where it is impractical to use superparameterization. Since global CRMs are the closest analog to superparameterization, they offer a promising conduit, along with idealized models.

In our earlier experiments with climatological SSTs (Randall et al. 2003; Khairoutdinov et al., 2005), the MMF simulations showed a robust MJO with a realistic structure. Although quite encouraging, those early experiments were relatively short, each about year and half, with just a few MJO events. Recently, we performed an AMIP-style integration using prescribed monthly-mean SST and sea ice datasets from September 1, 1985 to September 1, 2004, i.e., a total of simulated 19 years. Thus, the MJO statistics as simulated by the MMF over 18-year period was compared with statistics derived from the similarly lengthy observations. The longer records make the comparison more robust. Figure 6 shows the wavenumber-frequency spectra outgoing longwave radiation (OLR) and zonal component of the wind at the 850 mb averaged over the 15^{o}S-15^{o}N latitudinal belt. This spectra were obtained using the methods of Wheeler and Kiladis (1999; hereafter WK) who analyzed the tropical subseasonal variability using the ratio of the raw spectral power to the power of a “background spectrum,” which is simply a sufficiently smoothed raw spectrum. Positive zonal wavenumbers indicate eastward propagating disturbances; the lines in the figure are the theoretical dispersion curves for the shallow-water equations for selected equivalent depths.

In the observations, the MJO occupies the spectral window of eastward wavenumbers of 1-4 and periods greater than 30 days. The eastward moving Kelvin waves and westward moving Rossby waves follow the theoretical dispersion curves corresponding to a 25-m equivalent depth. In MMF simulation, all three of these modes are captured quite well, especially in OLR. The Kelvin wave is a bit weak but appears to propagate at about observed speed. As in observations, there is a clear frequency separation of the Kevin-wave from the MJO. In contrast, the simulation produced with the standard CAM3 lacks most of the MJO power with no clearly preferred wavenumber, and although the Kelvin wave has a strong amplitude its phase speed is too fast, corresponding to an equivalent depth of more than 50 m. For the 850-mb zonal wind, the wavenumber-frequency spectra for the MMF bears a strong resemblance to that of the ERA40, characterized by a distinct spectral break between the MJO and slow-moving Kelvin waves. In the CAM, little power is seen in the MJO spectral space and the Kelvin wave is distinctly faster than observed. The similarity in the shapes of these wavenumber-frequency plots to those seen for the observations and the MMF OLR are evidence of strong convective coupling. Furthermore, the resemblance of the MMF precipitation spectrum (not shown) to that of the GPCP data indicates that MMF precipitation, and not just cloud fields, is organized on a large scales similar to those found in nature.

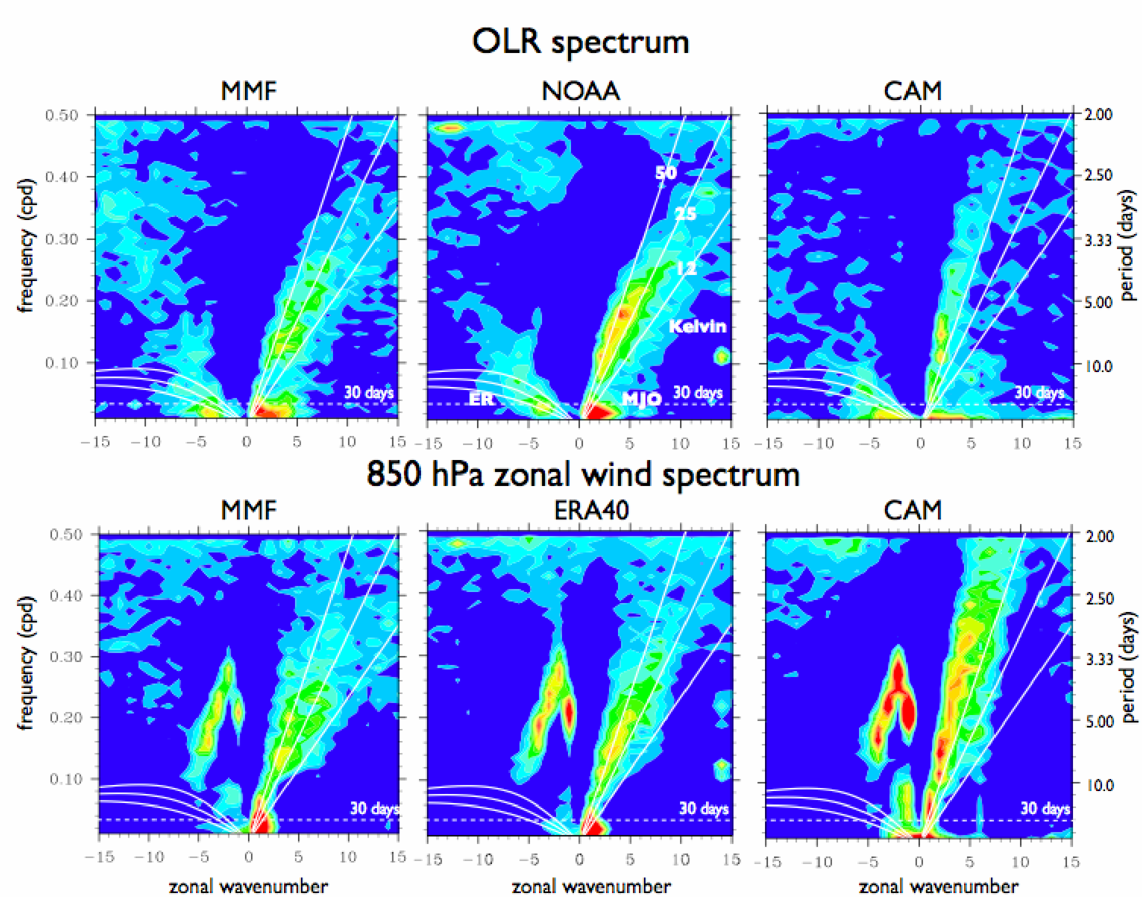

Figure 6: The symmetric raw spectral power divided over the background power (signal-to-noise ratio spectrum) for the OLR (top raw) and zonal wind component at 850 mb (bottom raw) as (left) simulated by the MMF, (middle) derived from observations, and (right) simulated by the CAM3. Superimposed are the theoretical shallow-water dispersion curves for the equatorial Rossby and Kelvin waves for the equivalent depths of 12, 25, and 50 m. Contour interval is 0.1 with contours beginning at 1. Observations are: 1979-2004 NOAA AVHRR interpolated OLR data, and the ECMWF ERA-40 reanalysis.

Figure 7 shows the geographical distribution for the simulated and observed OLR variance of the disturbances associated with the MJO averaged for the boreal winter, boreal summer, and the annual average. Overall, the pattern of OLR variability is well reproduced by the MMF. As in the observations, the simulated MJO is mostly confined to the Indian Ocean and the western Pacific. Also, the MJO is considerably stronger during the boreal winter, with the maximum activity just north from Australia, as observed. During boreal summer, the MJO can propagate much further eastward, just north from the equator, all the way to the Gulf of Mexico. This is also well captured by the MMF.

However, the magnitude of the OLR variance is overestimated by about 50% (please note that different color bars are used for the MMF and observations). Unlike most of GCMs which typically produces an MJO which is too weak, the MMF tends to make the MJO stronger than observed.

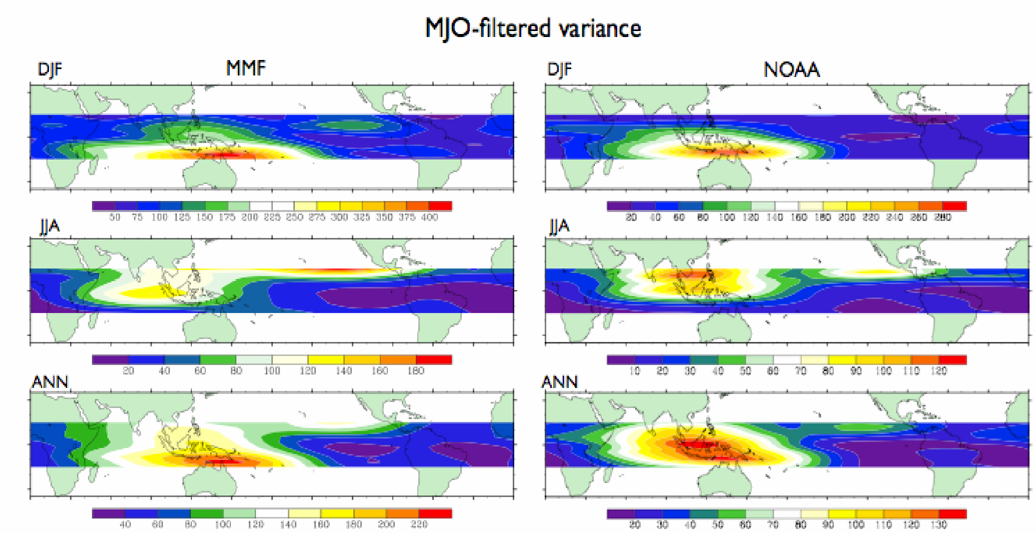

Figure 7. The geographical distribution of the for the MJO-filtered OLR variance averaged for the (top) boreal winter , (middle) summer, and (bottom) annual mean for (left) MMF simulation and (right) NOAA observations.

The interannual and seasonal variability of the simulated and observed MJO is demonstrated by Fig. 8. One can see that the strength of the simulated MJO varies quite a bit from year to year as also seen in the observations. In the MJO simulation, the periods with the strongest MJO events tend to occur during boreal winter and early spring, and the weakest MJO events generally occur during late boreal summer, in agreement with observations.

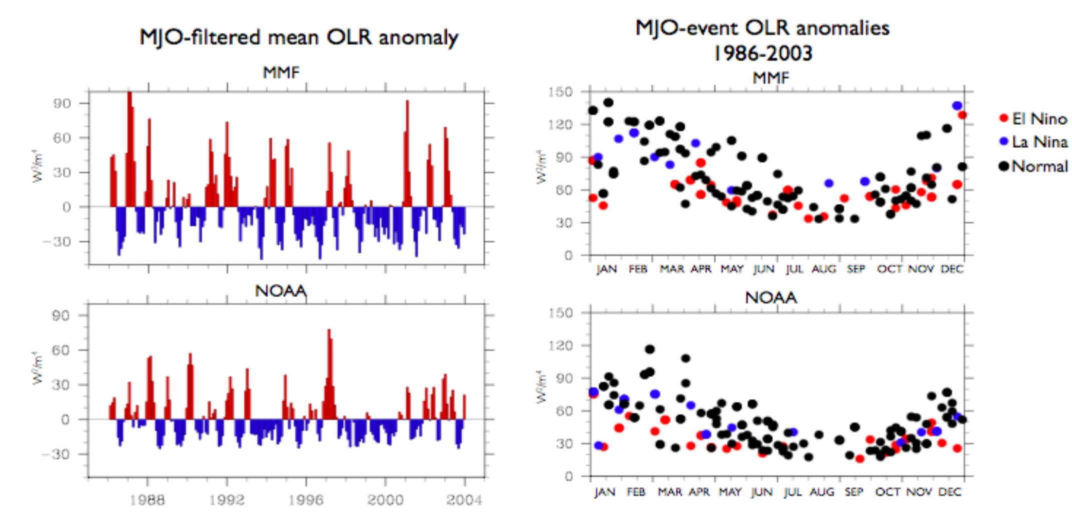

Figure 8. MJO-filtered OLR variance for the (top) MMF simulation and (bottom) NOAA observations as a multi-year time series with the multi-year mean subtracted (left) and as a seasonal cycle (right).

3. Research Objectives, Strategy, Priorities, and Actions

3.1 Objectives

- To understand the role of multi-scale convective organization in the context of the MJO.
- To evaluate high-resolution multi-scale numerical simulations with emphasis on integrated satellite data and new reanalysis products.
- To take the analysis of MMF and Global Cloud-system Resolving Models (GCRM) to the next level of complexity (e.g., vertical structure, distribution of cloud types etc).
- To improve the representation of the MJO in GCM and global NWP models

3.2 Strategy

- Conduct comprehensive evaluations of MMF and global CRM simulations.
- Use satellite observations to evaluate MJO realizations at a 'process level'
- Use the ECMWF new reanalysis products (T255, from 1989-2007) for model validation, initial and lateral boundary conditions for numerical simulations; compare these analyses with comparable satellite products.
- Develop advanced multi-scale theoretical-dynamical models of the MJO and use them to interpret numerical simulations.
- Apply the new metrics from the US CLIVAR MJO Working Group to evaluate the MJOs generated by MMF.
- Investigate (in detail) sub-seasonal variability of convection in CAM, particularly those associated with convective parameterization.
- Understand why MMF and global CRMs over-predict the intensity/amplitude of MJOs, compared to contemporary global models which under-predict them.

3.3 Research priorities and numerical experiments

- Conduct case studies of MJO events on the scale of the Indian Ocean/Western Pacific basin using NWP models and nested models forced at lateral boundaries by global model analysis; compare with satellite measurements (e.g., A-train, Cloudsat, Calipso, TRMM, AIRS etc).

- Conduct a benchmark 1 km grid-spacing nested simulation of the entire tropics when sufficient computational resources are available.

- Hindcasts using MMF (AMIP-type climate resolution) of observed MJO events and compare with CAM

- Simulate the MJO in an aquaplanet version of MMF having a zonally variable SST distribution

- Examine properties of the MJO in the prototype 1.25 degree CAM.

- Match the numerical experiment plan with the computing resource allocation schedule.

- Investigate the role of convective momentum transport (CMT) and mesoscale momentum transport (MMT) in the MMF, and use multi-scale analytic models to interpret the results.

3.4 Action items for the August CMMAP meeting

- Ensure that the MJO Focus Theme is consistent with the CMMAP Strategic Implementation Plan e.g., improvement of NWP and climate models (D. Randall).

- Presentation of the new ECMWF reanalysis products (M. Miller or designee).

- Presentation of satellite analysis products for model validation (C. Kummerow).

- Analyze vertical structure of MMF-simulated MJOs and compare with observations (CSU students: Jim Benedict & Kate Thayer-Calder).

- Design a prototype nested-domain “nature” simulation of an MJO event over the Indian Ocean for comparison with satellite measurements (M. Moncrieff).

- Hindcast and aquaplanet simulations of the MJO (M. Khairoutdinov).

- Develop ice content retrieval algorithm for MJO events (A. Heymsfield).

- Collaborate with the Low Cloud Feedback & Turbulence Theme and Deep Convection Focus Theme.

- Complete the White Paper on the MJO Focus Theme (M. Moncrieff).

Websites

ICTP Workshop on organized tropical convection and the MJO:
http://cdsagenda5.ictp.trieste.it/full_display.php?ida=a04205

CLIVAR Sub-seasonal MJO Working Group:
http://www-pcmdi.llnl.gov/projects/amip/ape/

AMIP-type Aqua-Planet Model Inter-comparison Project:

http://www.usclivar.org/Organization/MJO_WG.html

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