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# Coupled Ocean-Atmosphere Dynamics and Predictability of MJO's

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## LONG-TERM GOALS

Our long-term goal is to develop a coupled ocean-atmosphere model that has significant and quantified skill in predicting the evolution of Madden-Julian Oscillations (MJO's), which is highly relevant to ONR long-term objectives. This requires developing a better understanding of the sensitivities of the atmospheric circulation associated with MJO's to small-scale SST anomalies, regional-scale SST anomalies, the diurnal cycle, surface waves, upper-ocean mixing, and various other aspects of ocean-atmosphere feedbacks.

## OBJECTIVES

The objectives and immediate scientific goals of the proposed research are:

1. *Develop and test the Scripps Coupled Ocean-Atmosphere Regional (SCOAR) model for MJO predictability and feedback process studies;*
2. *Develop and test a WRF-ROMS regional coupled model (SCOAR2) for MJO predictability and feedback process studies;*
3. *Test the NCAR CCSM coupled model for MJO predictability and in feedback process studies.*

## APPROACH

We are working as a team to study MJO dynamics and predictability using several coupled models in the Indo-Pacific sector as team members of the ONR DRI associated with the DYNAMO experiment in the Indian Ocean. This is a fundamentally collaborative proposal that involves Miller and Waliser as well as Dr. Hyodae Seo of the Woods Hole Oceanographic Institution, Prof. Ragu Murtugudde of the University of Maryland, and Dr. Markus Jochum (formerly of NCAR, now at the Niels Bohr Institute of the University of Copenhagen). The results presented here include work by all the team members and their students (Mr. Aneesh Subramanian, SIO; Mr. Ankur Gupta, SIO), research staff (Xianan Jiang, JIFRESSE) and external collaborators, because we have discussed, instigated and synthesized each others' research activities and results by keeping in close contact via email and by meeting at various conferences during the past year. Additionally, through Waliser's role as co-chair of both the WCRP-WWRP/THORPEX YOTC Science Team and the MJO Task Force

(www.ucar.edu/yotc/mjo.html), we work to leverage from those activities as well as to make sure our research outcomes are positioned to contribute to the overall objectives of those programs.

The primary questions we are addressing are:

*1) Do the effects of mesoscale SST on the surface fluxes of heat and momentum introduce significant changes in the amplitude, structure, wavenumber and frequency of the MJO's?*

This can be addressed by running models in both coupled and uncoupled mode and comparing the structures of the MJO's produced. The focus here is on how oceanic mixed layer coupling with the atmospheric boundary layer transfers heat and energy to the overlying large-scale atmospheric MJO dynamics, and then on how changes to the mixed layer induced by diurnal cycle forcing and surface gravity wave processes alter these effects.

*2) What are the consequences on the predictability of regional MJO development when mesoscale ocean-atmosphere coupling is allowed to influence the evolving MJO?*

Does the intrinsic variability (e.g., atmospheric storms) in the domain increase with these mesoscale feedbacks present, thereby lowering the predictability of MJO regional response? Or do the boundary conditions and large-scale dynamics of MJO strongly control the regional response? These uncertainty issues can be quantified by comparing sensitivities to initial conditions, boundary conditions, and physics parameterizations using models in coupled versus uncoupled mode and in high-resolution versus coarse-resolution mode, for both perfect model experiments and runs compared with observed events.

## WORK COMPLETED

Since the start of this current award in spring, 2010, we have contributed to the following subset of accomplishments of the multi-institutional team:

- **a.** Constructed a regional version of SCOAR (RSM-ROMS) in the Indo-Pacific sector (led by Seo, WHOI)
- **b.** Constructed a regional version of WRF in the Indo-Pacific sector (led by Murtugudde, UMd)
- **c.** Constructed a new version of SCOAR2 (WRF-ROMS) in the Indo-Pacific sector (led by Seo, WHOI)
- **d.** Run and analyzed SCOAR and SCOAR2 to determine how well MJO's are simulated. (led by Seo, WHOI, with Gupta, SIO)
- **e.** Run SCOAR2 in downscaling mode for the 2$^{nd}$ MJO event during the DYNAMO period (led by Seo, WHOI, with Miller, SIO)
- **f.** Run and analyzed WRF-ROMS for several years to determine how well MJO's are simulated (led by Strack, UMd, and Seo, UH)
- **g.** Run and analyzed CCSM4 to determine how well MJO's are simulated (led by Subramanian, SIO, Jochum, NCAR, and Miller, SIO)
- **h.** Analyzed how MJO's in CCSM4 are affected by a global change scenario of the 21$^{st}$ century. (led by Subramanian, SIO and Jochum, NCAR)

**i.** Tested the sensitivity of CCSM3 to convective parameterizations (led by Zhou, Columbia, and Murtugudde, UMd)

**j.** Developed a mixed-layer budget analysis of the Indian Ocean based on ECCO, including the DYNAMO location, to serve as a baseline for the new observations (led by Waliser, JPL)

**k.** Investigated the impact of MJO on surface chlorophyll concentration and its feedback to the upper-ocean mixed layer heat budget (led by Murtugudde, UMd, and Waliser, JPL)

**l.** Attended ONR PI meetings associated with the DYNAMO experiment (led by Miller, SIO)

**m.** Conducted teleconference group meetings with the MJO Task Force (TF), refined the near-term objectives of that activity, and in June 2010 held a TF meeting and co-organized an MJO workshop joint with the CLIVAR Asian-Australian Monsoon Panel (led by Waliser, UCLA/JPL)

## RESULTS

The following summarizes our most interesting and important results during the third year of collaborative research under this research project.

*1. SCOAR2 MJO modeling*

*a. MJO characteristics of SCOAR2 in coupled and uncoupled mode*

We successfully coupled WRF to ROMS, and have dubbed the new model SCOAR2. The long-term characteristics of the simulated MJOs in SCOAR2 (with 0.38° horizontal resolutions) and the impact of interactive SSTs are subsequently examined in two twin experiments differing presence of air-sea interaction, **COUPLE**: Ocean-atmosphere coupling included every day for Oct-Mar. 2005-2010; and **CONST-SST**: Time-averaged mean SST computed from COUPLE and prescribed forcing for the WRF model over the same time period. These two runs are now being compared with the observed characteristics of MJOs (Seo et al., 2012).

Fig. 1 compares observed (left) and simulated (center and right) wavenumber-frequency spectra of the symmetric component (2.5°N-10°N) of the outgoing longwave radiation (OLR) and 10-meter surface zonal wind (U10) from observations, COUPLE and CONST-SST. SCOAR2 COUPLE (Fig. 1 middle) contains the enhanced spectral density in OLR and U10 fields over the broad band of the planetary wavenumbers k=1-4 and the frequencies w=0.006~0.055 cpd (18 to 166 days), which is in good agreement with the observations (Fig. 1a-b). It should be also noted that the spectral power in OLR and U10 is slightly enhanced for the coupled case compared to the constant SST case (Fig. 1 right), suggestive of the amplifying impact of intraseasonal variability by the interactive SSTs.

Fig. 2 illustrates the 5-winter averaged lead-lag correlation coefficients of OLR (contours) and rainfall (shades) with the reference OLR value averaged over 10°S-10°N, 75°E-100°E. The OLR and rainfall anomalies from COUPLE (Fig. 2b) and CONST_SST (Fig. 2c) both exhibit approximately 40-day oscillations as the observations suggest (Fig. 2a), along with the apparent co-propagation between the two. The phase speed, based on these Hovmoeller diagrams, is roughly 5 m/s (blue straight lines), which is very close to the observed values, indicating a significant convective coupling in the MJO rather than free linear Kelvin waves being dominant.

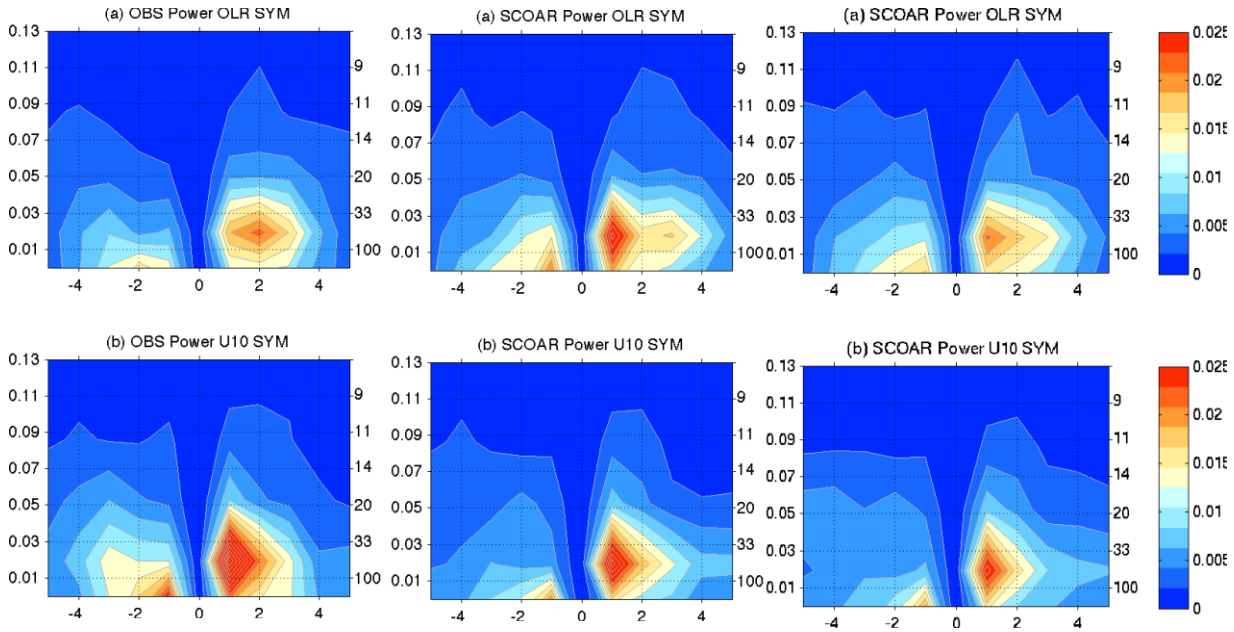


***Figure 1. (Left) October-March (2005 to 2009) wavenumber-frequency spectral density of the symmetric component (2.5N-10N) of (a) NOAA OLR ($W^2/m^4$) and (b) NCEP U10 ($m^2/s^2$). (Middle) As in (left) except from SCOAR2 COUPLE and (Right) SCOAR2 CONST_SST.***

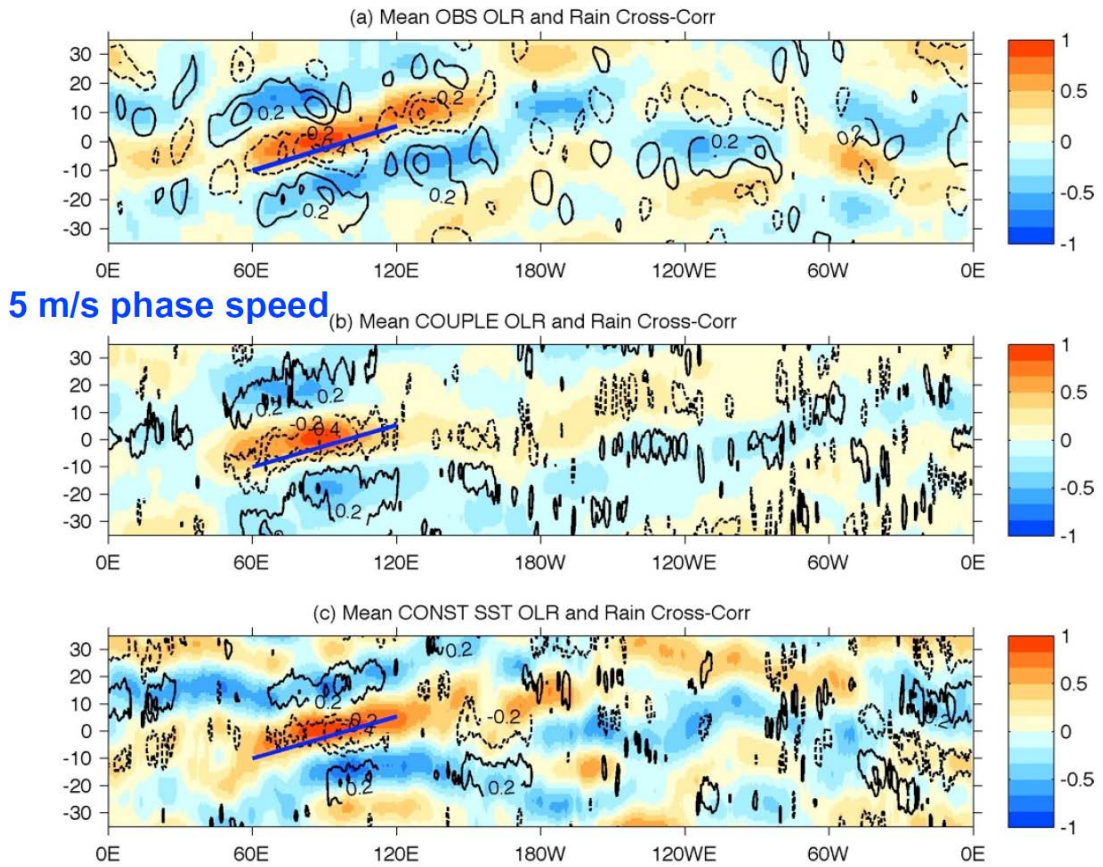


***Figure 2. Sample results from comparing COUPLE (middle) and CONST SST (bottom) runs of SCOAR2 with observations (top). Lag correlation of reference OLR (75E-100E, 10S-5N) with the rainfall (color) and OLR (contours), based on a 5-year average. 5 m/s phase speed shown by the blue line.***

In order to further verify if the extracted MJO modes are a physically meaningful mode of variability and distinct from noise, the combined EOFs derived from the filtered OLR and U10 are projected onto the unfiltered daily OLR fields (seasonal cycle removed). The corresponding power spectra of the unfiltered PCs show a significant (above 95% level) peak at 30-80 day band both in the observations (top) and the model runs (middle and bottom), although the power is much more pronounced and significant with an interactive SST case in comparison to a constant SST case.

Through this long-term sensitivity tests, we have established that SCOAR2 is capable of capturing the intraseasonal convective anomalies in rainfall and OLR, and the associated atmospheric circulation features. In the next section, we examine the MJO simulations during DYNAMO period and test if the model is capable of reproduce the observed coupled boundary layer process identified from the in situ data during the onset of the 2nd MJO event in November-December 2011.

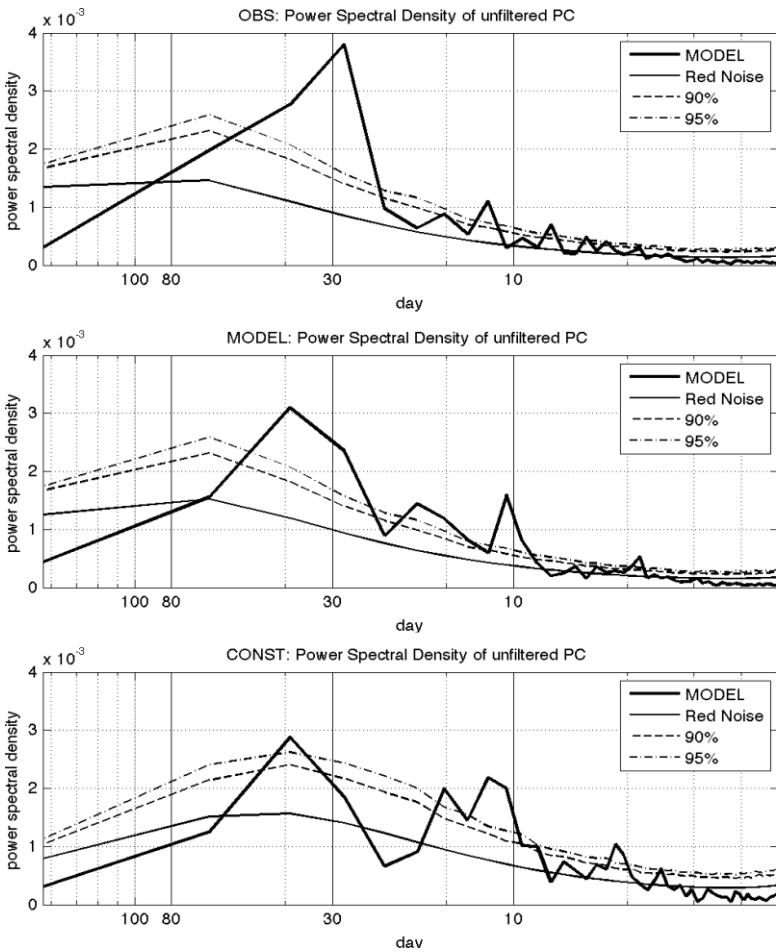


***Figure 3. Power spectral density of PC1 from the (a) observations, (b) COUPLE and (c) CONST_SST projected onto the respective unfiltered daily data. Dashed lines show the red noise spectrum and upper 90% and 95% confidence limits on this red noise spectrum.***

*b. Hindcast coupled downscaling of the DYNAMO period*

We have begun a series of hindcast downscaling experiments with SCOAR2 during the onset of the 2nd MJO event during DYNAMO. Simulations consist of a series of 48-hour coupled integrations with an hourly coupling initialized daily at 0000 UTC. The initial 24 hours are taken as model spin-up time for the surface boundary layer process. Initial conditions for the WRF and ROMS are taken from the ERA-Interim Reanalysis and the ECCO ocean state estimation. Model output beginning with hour 24 of the individual simulations is connected into a month-long representation.

The Hovmoeller diagrams of the observed precipitation, 850 mb zonal wind and near-surface current anomalies from the observations indicate that the convective precipitation anomaly initiates on 27NOV2011, which then propagates eastward at 5m/s. While somewhat overestimating the rainfall anomaly, the model produces the realistic eastward propagating convective rainfall signal with the comparable phase speed to the observations. The intensified easterly (westerly) 850 mb zonal wind anomaly precedes (follows) the MJO convection, indicating a quadrature phase relationship between wind and convection associated with MJO. The westerly anomaly after the onset of this MJO event triggers large amplitude eastward surface current anomalies at the equator (the Wyrtki Jets) exceeding 1 m/s as observed from DYNAMO.

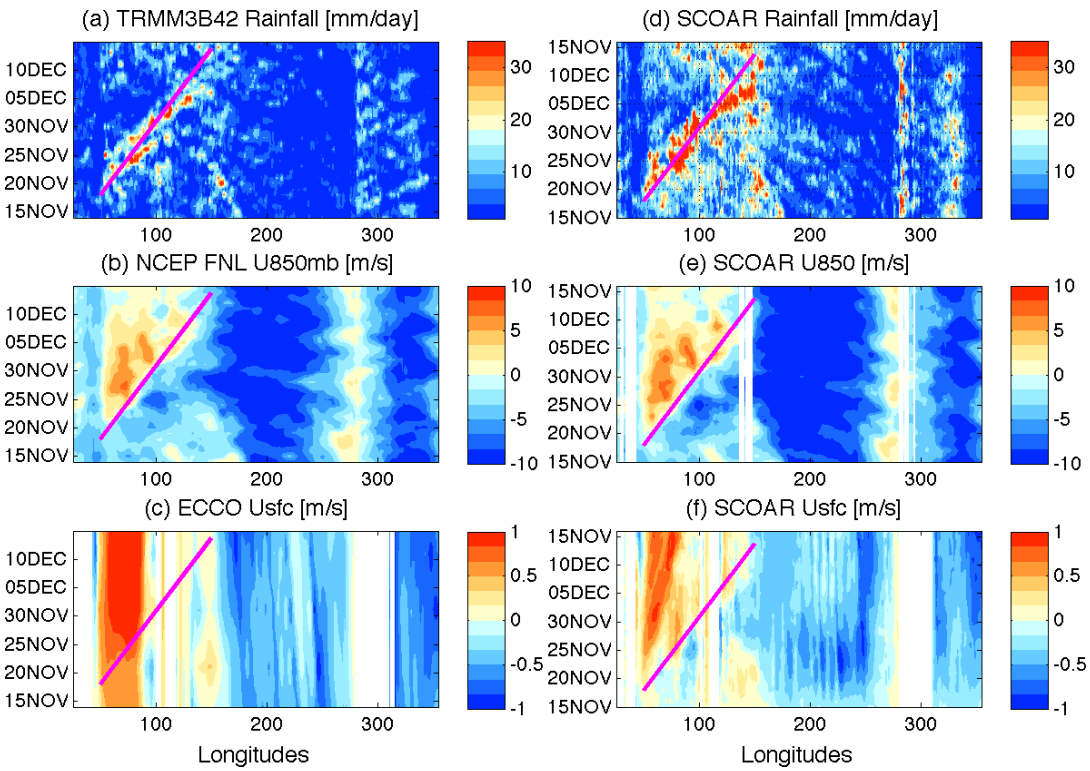


***Figure. 4. Longitude-time diagrams of (left) observations and (right) model showing (top) precipitation rate (mm/day), (middle) 850mb zonal wind (m/s) averaged in 10°S-10°N, and (bottom) ocean surface current (m/s) at the equator (1°S-1°N). The straight diagonal lines, identical in all panels, denote the eastward propagating speed of 5 m/s beginning at the onset of rainfall event from (a).***

The co-evolution of coupled boundary layer process is further depicted in Fig. 5 showing the normalized time-series of rainfall, latent heat flux (LH), OLR, SST and 10-m zonal wind averaged over 10° long. by 20° lat. box centered on the site occupied by the Revelle. Two peaks in rainfall anomalies on 24NOV2011 and 28NOV2011 (black), which are reasonably well captured by the model, are accompanied by the simultaneous maxima in latent heat release from the ocean (green) and the minima in OLR (blue), suggestive of the moist-convection process. SST (red) is warmer before the convection corresponding to the anomalous easterly wind (cyan), while cooler afterwards coincident with the westerly wind anomalies. This salient feature of MJO-ocean interactions illustrated by the space-time variations in coupled boundary layer process is overall reasonably well simulated by the model.

Further analysis of the model solution and validation against the DYNAMO data needs to be carried out in subsequent research. Through the sensitivity tests, we will also explore the response in coupled boundary layer process associated with MJO's to the observed features during DYNAMO, such as the

freshwater pool, dry air intrusion, heat flux variations on diurnal time-scale, upper ocean mixing and Wyrtki Jets, etc.

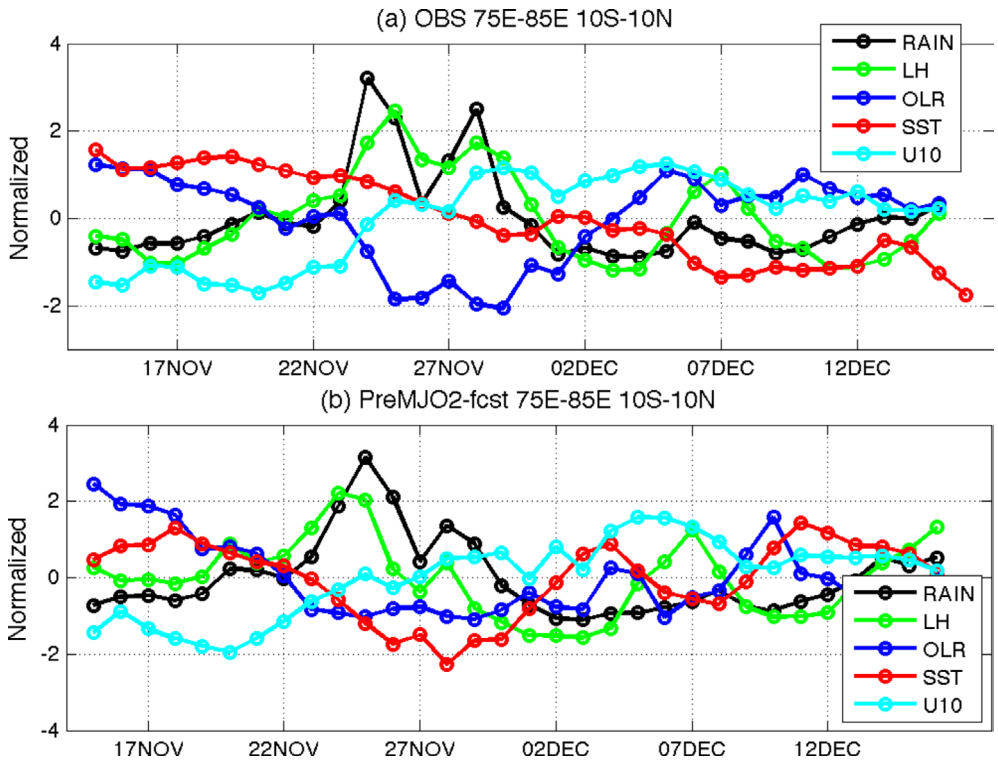


***Figure 5. Normalized time-series averaged over the area 75°E-85°E, 10°S-10°N from (top) observations and (bottom) model, showing (black) rainfall, (green) latent heat flux, (blue) OLR, (red) SST, and (cyan) 10-m zonal wind speed.***

*2. CCSM MJO modeling*

We completed our initial assessment of the ability of the Community Climate System Model-4 (CCSM-4) to represent the MJO. The results are now published (Subramanian et al., 2011) in the special issue of *Journal of Climate* devoted to the recent release of CCSM4. We used the US CLIVAR MJO Working Group prescribed diagnostic tests (Waliser et al., 2009) to evaluate the model's mean state, variance and wavenumber-frequency characteristics in a 20-year simulation of the intraseasonal variability in zonal winds at 850 hPa (U850) and 200 hPa (U200) and Outgoing Longwave Radiation (OLR). Unlike its predecessor, CCSM4 reproduces a number of aspects of MJO behavior more realistically as detailed in Subramanian et al. (2012).

We have continued the study of MJO in CCSM-4 (which has a better representation of MJO than CESM) by considering the sensitivities of MJO activity in an altered background state due to a global warming scenario compared to present conditions (Subramanian et al., 2012, in preparation). The extreme global warming climate is defined as the Representative Concentration Pathways (RCP) 8.5 scenario, which reflects the socio-economic pathway that reaches a radiative forcing of 8.5 W/m2 by the year 2100.

After computing the MJO Index for both the forced runs, the frequency of MJO amplitude occurrence in the 20th century and the RCP8.5 forced case is evaluated and presented in Figure 6. The number of days of highest MJO amplitude events in the global warming scenario is significantly higher than the

20th century run. The weaker MJOs of about the amplitude 2 (mean amplitude for both the periods) decreases in the global warming scenario. This is consistent with previous studies showing that the extreme events are amplified in a more active hydrological cycle due to a warmer atmosphere.

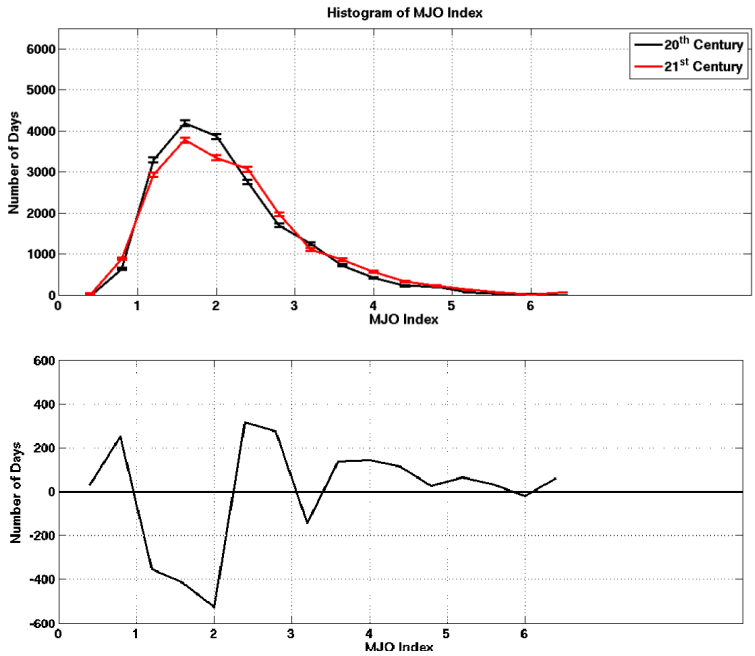


***Figure 6. MJO Activity in the present vs future climate of RCP8.5 scenario. The number of days that the MJO exceeds the threshold amplitude is plotted as a line histogram in (top). The difference between the Present and Future MJO active days for each amplitude is plotted in (bottom).***

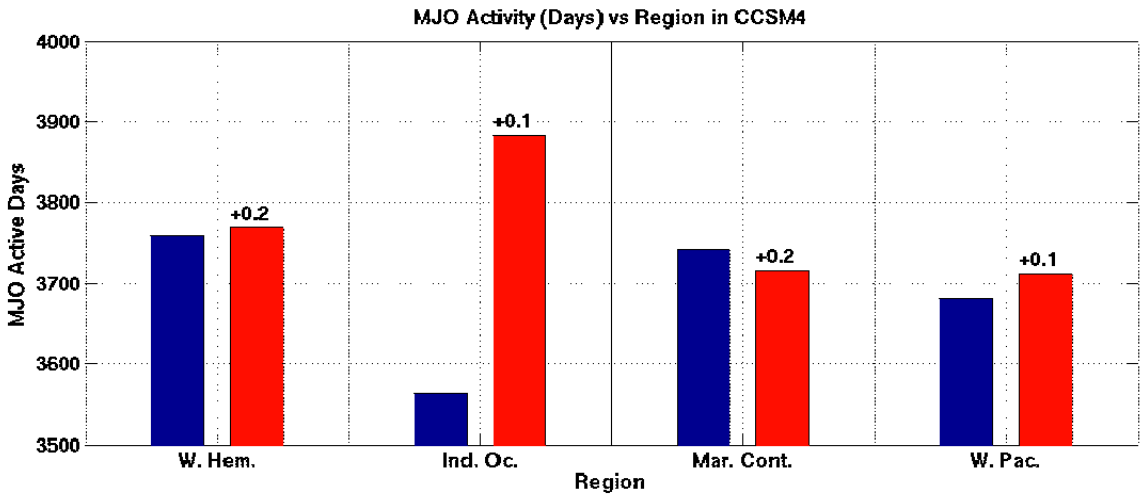


***Figure 7. Regional changes in amplitude for the MJO under the global warming scenario. Number of MJO active days in CCSM4 in the present climate (blue) is compared to the future climate (red) for the western Hemisphere, Indian Ocean, Maritime Continent and Western Pacific. The difference in mean amplitude (RCP8.5 - 20th century) is indicated on top of the red bars. The change in amplitude is always positive indicating that the average amplitude of the MJO increases in this simulated future climate scenario.***

The changes in the MJO active days (when the MJO amplitude is greater than 1) in different regions around the world (identified from the MJO phases) are shown in Figure 7. The mean amplitude of the MJO events in different phases in the RCP8.5 case is always greater than the mean amplitude in the 20th century climate. A particularly large increase in the number of active MJO days is identified for the Indian Ocean region, where the mean amplitude increases by 0.1, and the number of days increases by about 500. This is consistent with the large increase in variance of the intraseasonal precipitation found in the Indian Ocean for the RCP8.5 model case. There is a net decrease in the number of active MJO days over the Maritime Continent. The number of active MJO days in the Western Pacific also increases by about 100 days. This indicates higher amplitude MJO events occurring mostly in the Indian Ocean and some of them also propagating over into the W. Pacific. Additional work is required to assess the mechanisms controlling the propagation and structural changes in the MJOs associated with background mean climate changes.

An aquaplanet modeling study was initialized by Murtugudde with a Ph.D. student in the Indian Institute of Science, Bengaluru, using the latest version of the CCSM atmospheric model CAM. Symmetric SST forcing was prescribed in the tropics to show that when the maximum SSTs reach one Rossby radius of deformation, there is a switch from a single convergence on the equator to a double ITCZ structure and the separation of the weather and intraseasonal time-scales. The addition of a heat source representing land and the evolution of the ISOs are being investigated with the same model set up.

*3. MJO influences on oceanic chlorophyll and feedbacks*
*a. Observational study of surface Chlorophyll modulation by the MJO*

The MJO modulation of sea surface chlorophyll-a (Chl) examined initially by Waliser et al. (2005) is revisited by Jin et al. (2012a) with a significantly longer time-series of observations and a more systematic approach to characterizing the possible bio-physical interaction mechanisms underlying the MJO-Chl relationships. The MJO composite analysis of Chl and lead-lag correlations between Chl and other physical variables reveal regional variability of Chl and corresponding indicative temporal relationships among variables.

Along the path of the MJO convection, wind speed - a proxy for oceanic vertical turbulent mixing and corresponding entrainment - is most strongly correlated with Chl when wind leads Chl by a few days. Composite Chl also displays MJO influences away from the path of the MJO convection. The role of wind speed in those regions is generally the same for Chl variability as that along the path of the MJO convection, although Ekman pumping also plays a role in generating Chl variability in limited regions. However, the wind forcing away from the MJO convection path is less coherent, rendering the temporal link relatively weak. Lastly, the potential for bio-physical feedbacks at the MJO time-scale is examined. The correlation analysis provides tantalizing evidence for local bio-feedbacks to the physical MJO system. Plausible hypotheses for Chl to amplify the MJO phase transition are developed.

*b. Modeling study of the mechanisms of surface chlorophyll modulation by the MJO*

Previous studies analyzed ocean color satellite data and suggested that the primary mechanism of surface chlorophyll (Chl) response to the MJO is wind-induced turbulent mixing and the corresponding entrainment. In a study by Jin et al. (2012b), this hypothesis is examined with a bio-physical ocean model, focusing on near and subsurface processes ($z<200$m). As a whole, the model's mean Chl state is lower than observations except in the tropical Pacific basin, but seasonal variation is acceptable particularly in the tropical Indian Ocean. In this basin, the model can simulate surface Chl responses to the MJO consistent with the observational counterpart in terms of phase-by-phase anomaly evolution pattern.

Those Chl responses are mostly induced by surface wind forcing, which is consistent with previous studies. Based on case studies at selected grid points, it is revealed that, 1) entrained nutrients are the primary source to increase surface Chl concentration, and detrainment blooms are less common, 2) in limited region, Ekman pumping can effectively reduce Chl concentration, and 3) both entrainment / detrainment and Ekman pumping mechanisms rely on background states of nutrition distribution, so the same forcing can result in completely contrasting Chl responses depending on the background state including annual cycle and interannual variability.

*c. Modeling study of the improved mean state of surface Chlorophyll concentration by the MJO*

Previous modeling study suggested a possibility of the rectifying effect of the MJO on the surface Chl mean state to be increased. This hypothesis could not be tested there because of the experimental setup, which allows the MJO forcing for only 200 days. Jin et al. (2012c) build a whole year of MJO forcing including both the boreal winter and summer MJO, and force the OGCM for several decades to reach statistical equilibrium. The result is surprisingly improved in terms of surface Chl concentration in the tropical Indian Ocean. In this basin, when the MJO anomaly is added to the climatological forcing, surface Chl is comparable to the observations, particularly in the eastern equatorial Indian Ocean, while it is 1/1000 less concentration when the only climatological forcing is prescribed.

It is already known that the MJOs rectify the mixed layer depth (MLD) to be shallower at lower than intraseasonal time-scale (Waliser et al. 2003, 2004). By comparing the annual and seasonal means between the MJO and control simulations, we found that in most regions, the MJO forcing results in 1) consistently shoaled MLD, 2) also shoaled the isothermal depth (ITD) but more than the MLD, which translates to reduced barrier layer thickness (BLT), and 3) reduced vertical gradient of nutrient distribution in shallower than 100m depth. Considering all MJO signatures in the ocean, we hypothesize that the increased vertical mixing by the MJO diminishes stratification in the upper ocean, and allows more nutrients to reach the surface layer. With a series of case studies, we found that the variation of MLD and ITD produced by the periodic MJO enhances consecutive entrainment process, thus more nutrients from deeper layer is transported to the shallower layer like a conveyor belt.

These model results are also supported by the observations. When we calculate correlation coefficients between the seasonal activity of the intraseasonal variability (ISV; standard deviation of 30–120 days time filtered surface wind) and seasonal mean of surface Chl concentration, several significant signals are found in the eastern equatorial Indian Ocean, and the northwestern tropical Pacific, particularly in boreal summer. By comparing those correlated signals with observational climatological BLT, it is seen that the significant signals mostly overlap the region of approximately 20–40m BLT. Hence we suggest that those thicknesses of barrier layer can be affected by the atmospheric forcing of ISV, although there are several factors other than the ISV that can affect mean Chl concentration such as ENSO and Aeolian iron deposition.

*d. Modeling study of the effect of MJO on penetrative shortwave radiation and oceanic heat budget*

Surface Chl concentration controls the amount of shortwave penetrating into the ocean, and alters vertical heat distribution. Previous studies have argued that Chl can affect large-scale ocean dynamics and coupled climate variability. Jin et al. (2012d) quantify the variability of penetrating shortwave radiation along the MJO phases by comparing two experiments with and without attenuation depth (Hp) variation responding to the MJO forcing (hereafter Hp_MJO vs. Hp_Clim). Hp in the Hp_MJO is prognostic from the bio-coupled simulation forced by the MJO forcing, and this Hp is low-pass filtered to be prescribed in the Hp Clim run.

In terms of the mean state of the tropical Indian Ocean, we found two notable differences between the Hp_MJO and Hp_Clim simulations. When we calculate penetrating or absorbed shortwave radiation inside the ocean for a whole year, it is seen that the intraseasonal variation of Hp renders 1) less shortwave to be absorbed in the barrier layer, and 2) more shortwave to penetrate into deeper ocean below 100m (Fig. 8).

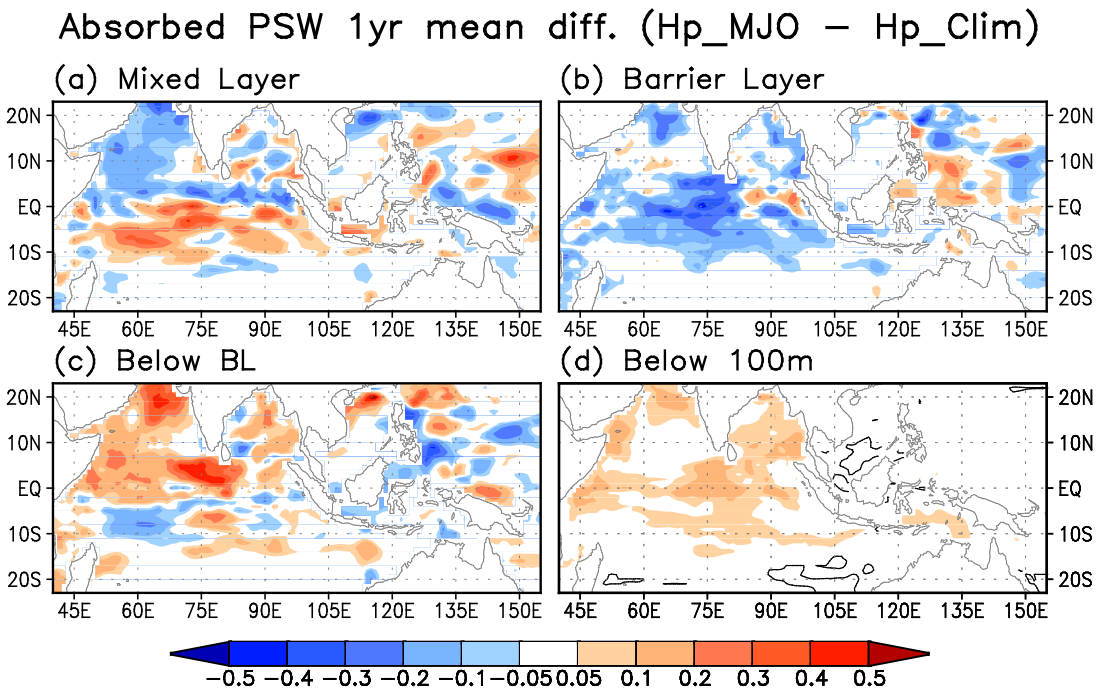


***Figure 8. The absorbed shortwave radiation in (a) the mixed layer and (b) the barrier layer. Penetrating shortwave radiation below (c) the barrier layer and (d) 100m depth. The values are averaged for one year, and the difference is calculated as the Hp_MJO run minus Hp_Clim run. The unit is W/m$^2$.***

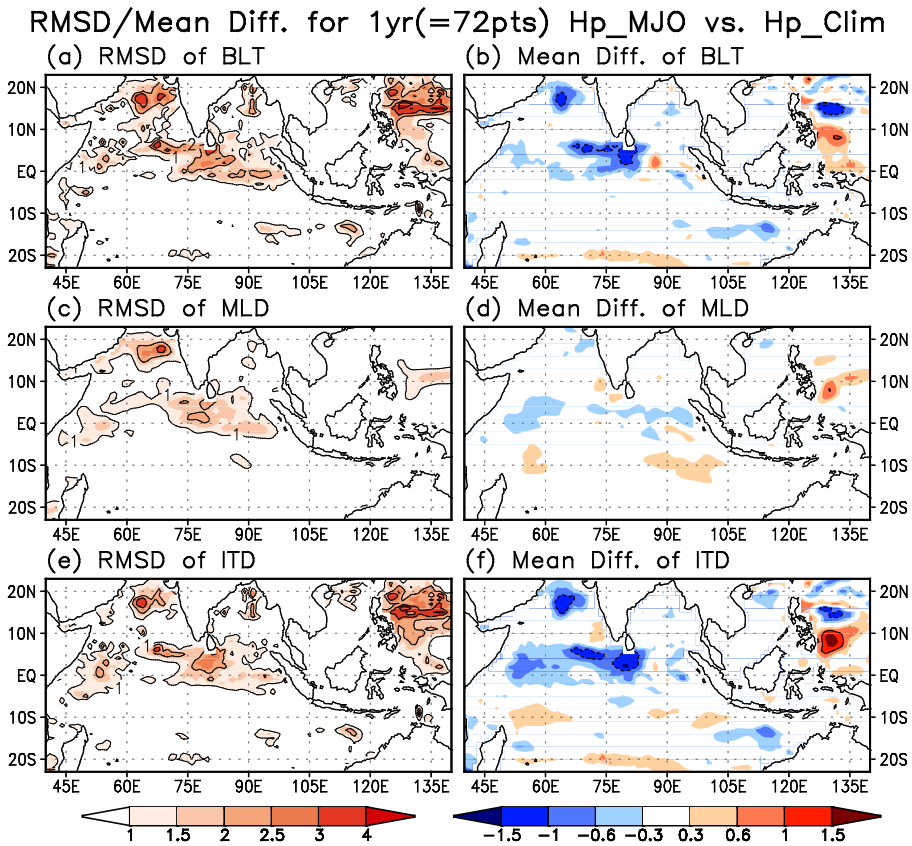


***Figure 9. Root-mean-squared-difference (RMSD; left column) and mean difference (right column) of (a, b) barrier layer thickness (BLT), (c, d) mixed layer depth (MLD), and (e, f) isothermal depth (ITD) for one year. The unit is meter.***

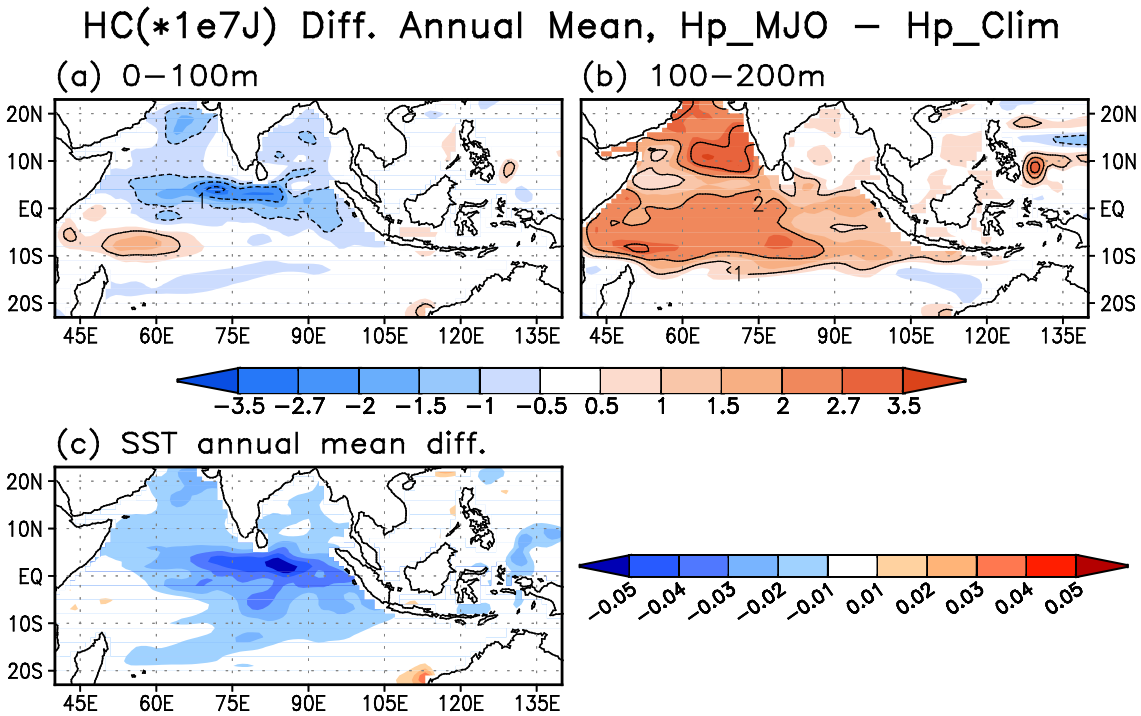


***Figure 10. Annual mean difference in heat content between the Hp_MJO and Hp_Clim simulations (a) for upper 100m, and (b) 100–200m. Unit is $10^7$ J/m$^2$. (c) Annual mean difference of SST (°K).***

Associated with the barrier layer, annual mean difference of barrier layer thickness (BLT) indicates that intraseasonally varying Hp results in a thinner BLT in the central tropical Indian Ocean, and the central Arabian Sea (Fig. 9b). Similar mean differences of the MLD and ITD show that the thinner BL is mostly because of shoaled ITD, while the MLD is quite similar between the Hp_MJO and Hp_Clim simulations (Figs. 9d and f). Root-mean-squared-difference (RMSD) results are mostly consistent with the pattern of the mean difference. These results suggest that asymmetric responses of penetrating shortwave to the MJO forcing lead to shoaled ITD in long-term average by less shortwave being absorbed in the isothermal layer.

Secondly, more shortwave radiation penetrating below 100m depth results in increased temperature and heat contents in the deeper ocean below 100m. Figure 10 shows that the increased annual mean heat contents (HC) in the layer of 100–200m is more than $2\times10^7$J/m$^2$ in the western-central tropical Indian Ocan, and up to $3.5\times10^7$J/m$^2$ in the southern Arabian Sea. We note that the corresponding mean temperature for 100m thick layer due to $1\times10^7$J/m$^2$ HC difference is approximately 0.024°K. Comparing Figs. 9a and b, it is seen that the decreased heat content in the upper layer is generally less in absolute magnitude than that in the deeper layer. Because the role of attenuation depth is essentially to control the vertical distribution of shortwave while total shortwave available to the ocean is the same in both simulations, the increased heat in the deeper layer should be balanced with the decreased heat in the upper layer. We hypothesize that the decreased heat in the upper layer is compensated by the heat flux at the ocean surface. The SST mean difference in Fig. 9c indicates a lower SST in the Hp_MJO simulation which translates to more heat flux from the atmosphere to the ocean, though the location of local minimum SST difference is shifted eastward compared to the that of HC difference in the upper layer. Overall, the Hp including intraseasonal variability alters vertical distribution of penetrating shortwave, and ultimately affects thermodynamic features in the tropical Indian Ocean.

*4. MJO kinetic energy budget*

Zhou et al (2012) establish a kinetic energy budget for the Madden-Julian Oscillation (MJO) in a three-scale framework. The three scales are the zonal mean, the MJO scale with wavenumbers 1-4, and the small scale with wavenumbers larger than 4. The dominant processes are synthesized in the following sketch. In the composite kinetic energy budget, the major balance at the MJO scale (KE') is between gain from the potential energy at the same scale (PE') and the work done by the pressure gradient force (PGF), which serves to move KE' away from the region of generation to nearby regions. This balance is qualitatively consistent with that in the classical linear Gill model. The major energy balance for the composite MJO event (namely conversion from PE' around 300 hPa and transfer to upper and lower troposphere by PGF) is similar to previous studies on tropical synoptic-scale disturbances, although the MJO is quite different from those synoptic-scale disturbances in many respects. A considerable amount of kinetic energy appears to dissipate near the tropopause because of cumulus friction, which is consistent with previous observations. Kinetic energy exchange between different scales is not a large component of the composite budget. There is a transfer of kinetic energy from the MJO scale to the small scale; that is, this multi-scale interaction appears to damp rather than strengthen the MJO. There is some variation in the relative importance of different terms from one event to the next. In particular, conversion from mean kinetic energy can be important in some events. In a few other events, the influence from the extra-tropics is pronounced (Fig. 11).

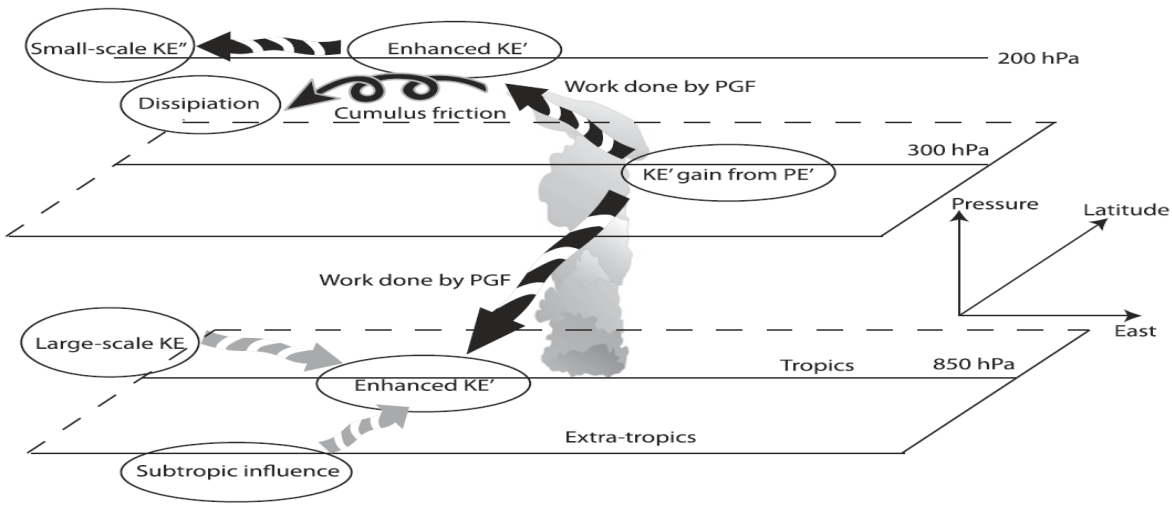


***Figure 11. Schematic of MJO kinetic energy budget.***

## IMPACTS/APPLICATIONS

We continue to be in contact with other DRI MJO modelers (e.g., S. Chen, NRL; C. Zhang and M. Ulate, Miami, T. Jensen, Stennis) for comparing simulations in the DYNAMO and YOTC frameworks.

We also continue to discuss our research results with Dr. Mark Swenson, Chief Scientist, FNMOC, to determine how effort might eventually be used to improve forecasting of MJO activity for practical use by the Navy. COAMPS, with specified SST, is currently available for practical regional forecasts. We expect our research to better reveal how ocean-atmosphere mesoscale coupling can influence extended-range (1 week to 1 month) forecasts of MJO variations, what atmospheric convective and SST feedback processes must be included in the model, how strongly oceanic and atmospheric boundary conditions influence the skill of regional MJO forecasts, and what upper-ocean conditions need to be observed to best execute these practical forecasts. As COAMPS soon will also include interactive ocean capabilities with NCOM in real-time mode, our results will additionally provide a comparison to COAMPS skill levels and help point the way in dealing with various regional modeling limitations as well. Extended-range dynamical forecasts in regions influenced by MJO are based on a dynamical process that has potentially useful skill levels. These forecasts are expected to be better than climatology and can contribute to establishing a smart climatology for these regions during times of MJO excitation. This forecast information can then be used in practical Naval operations planning. Dr. Swenson has agreed to continue to discuss our research results in the context of practical usefulness throughout the course of this research.

## RELATED PROJECTS

*WCRP-WWRP/THORPEX Activities*

Waliser served on the MJO Task Force and was a lead organizer in the MJO Diabatic/Vertical Structure Experiment. For details see www.ucar.edu/yotc/mjodiab.html and Petch et al. (2011). As of Sep 2012, there were 20, 11, 8 model contributions to the climatological, 20-day hindcast and 2-day hindcast experimental components, respectively. Preliminary results were presented at the Pan-GASS meeting in Sep 2012 (http://gewex.org/2012gass_conf.html). The final deadline for contributions is

Dec 2012, and the three initial papers, one for each component will be drafted by June 2013, with a summarizing paper drafted by fall 2013. Waliser also served on WWRP-WCRP Subseasonal Planning Group. This was a recent effort to develop a sub seasonal forecast database along the lines of TIGGE, but for subseasonal to seasonal time scales. An Implementation Plan has been developed and approved by the Joint Steering Committees (JSCs) of both WWRP and WCRP. It is expected that the planning group will be appointed as the steering group and the formal activity will start in 2013. A summary of the Implementation Plan will appear in the WMO Bulletin. Additional studies carried out relevant to the ONT-funded effort include the work by Jiang et al. (2012), Waliser et al. (2012) and Moncrieff et al. (2012).

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