

## Technical Report Series on Global Modeling and Data Assimilation

**Volume 25**

### Modeling, Simulation, and Forecasting of Subseasonal Variability

D. Waliser, S. Schubert, A. Kumar, K. Weickmann, and R. Dole

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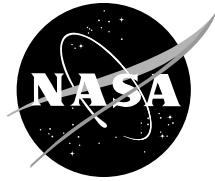
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### Volume 25

### Modeling, Simulation, and Forecasting of Subseasonal Variability

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## **Abstract**

A planning workshop on "Modeling, Simulation and Forecasting of Subseasonal Variability" was held in June 2003. This workshop was the first of a number of meetings planned to follow the NASA-sponsored workshop entitled "Prospects For Improved Forecasts Of Weather And Short-Term Climate Variability On Sub-Seasonal Time Scales" that was held April 2002. The 2002 workshop highlighted a number of key sources of unrealized predictability on subseasonal time scales including tropical heating, soil wetness, the Madden Julian Oscillation (MJO) [a.k.a Intraseasonal Oscillation (ISO)], the Arctic Oscillation (AO) and the Pacific/North American (PNA) pattern. The overarching objective of the 2003 follow-up workshop was to proceed with a number of recommendations made from the 2002 workshop, as well as to set an agenda and collate efforts in the areas of modeling, simulation and forecasting intraseasonal and short-term climate variability. More specifically, the aims of the 2003 workshop were to: 1) develop a baseline of the "state of the art" in subseasonal prediction capabilities, 2) implement a program to carry out experimental subseasonal forecasts, and 3) develop strategies for tapping the above sources of predictability by focusing research, model development, and the development/acquisition of new observations on the subseasonal problem.

The workshop was held over two days and was attended by over 80 scientists, modelers, forecasters and agency personnel. The agenda of the workshop focused on issues related to the MJO and tropical-extratropical interactions as they relate to the subseasonal simulation and prediction problem. This included the development of plans for a coordinated set of GCM hindcast experiments to assess current model subseasonal prediction capabilities and shortcomings, an emphasis on developing a strategy to rectify shortcomings associated with tropical intraseasonal variability, namely diabatic processes, and continuing the implementation of an experimental forecast and model development program that focuses on one of the key sources of untapped predictability, namely the MJO.

The tangible outcomes of the meeting included: 1) the development of a recommended framework for a set of multi-year ensembles of 45-day hindcasts to be carried out by a number of GCMs so that they can be analyzed in regards to their representations of subseasonal variability, predictability and forecast skill, 2) an assessment of the present status of GCM representations of the MJO and recommendations for future steps to take in order to remedy the remaining shortcomings in these representations, and 3) a final implementation plan for a multi-institute/multi-nation Experimental MJO Prediction Program.

# I. Introduction

A workshop was held in April of 2002 that brought together a wide range of experts in the Earth Sciences to focus on the subseasonal prediction problem (Schubert et al. 2002). This included over 100 scientists with specialties in areas that included stratospheric dynamics, hydrology and land surface modeling, the monsoons, the Madden-Julian Oscillation (MJO) and other tropical variability, extratropical variability including extratropical-tropical interactions, coupled atmosphere-ocean-land modeling, weather prediction, seasonal prediction, and various aspects of statistical modeling, analysis, and prediction. The goals of that workshop were to discuss the "state of the art" in predictive skill on time scales of 2 weeks to 2 months, to determine the potential sources of "untapped" predictive skill, and to make recommendations for a course of action that will accelerate progress in this area.

One of the key conclusions of that workshop was that there is compelling evidence for predictability at forecast lead times substantially longer than two weeks. Tropical diabatic heating and soil wetness were singled out as particularly important processes affecting predictability on these time scales. Predictability was also linked to various low-frequency atmospheric "phenomena" such as the annular modes in high latitudes (including their connections to the stratosphere), the Pacific/North American (PNA) pattern, and the Madden Julian Oscillation (MJO). The latter, in particular, was highlighted as a key source of untapped predictability in the tropics and subtropics, including the Asian and Australian monsoon regions. Among the four key recommendations of that workshop were the following:

- a)** That a coordinated and systematic analysis of current subseasonal forecast skill be conducted by generating ensembles of 30-day hindcasts for the past 30-50 years with several "frozen" AGCMs
- b)** That a series of workshops be convened focused on modeling the MJO, and that a coordinated multi-nation/multi-model experimental prediction program be developed focused on the MJO

In order to follow-up on the above two recommendations, a second workshop was held on June 4-5 2003 at the University Inn and Conference Center at the University of Maryland in College Park, Maryland. In this case, there were over 80 attendees (see Appendices I and II) that included both national and international participants. The agenda (see Appendix III) was devoted to establishing the framework and/or implementation plans for the subseasonal research issues and prediction activities highlighted in the above recommendations. The workshop was supported by the NASA Global Modeling and Assimilation Office and a subset of the U. S. CLIVAR inter-agency group (IAG), namely the NASA Global Modeling and Analysis Program (Tsengdar Lee), the NOAA Office of Global Programs (Ming Ji), and the NSF Climate Dynamics Program (Jay Fein). The workshop organizing committee consisted of Siegfried Schubert (co-chair, NASA/DAO and NSIPP), Duane Waliser (co-chair, SUNY/Institute of Terrestrial and Planetary Atmospheres), Randall Dole (NOAA/Climate Diagnostics Center), and Arun Kumar (NOAA/Climate Prediction Center).

This document summarizes the proceedings of the workshop. In the following section we present summaries of each session. A brief summary discussion is given in section III, along with a number of recommendations for future courses of action.

## II. Summary of Sessions

### A. Subseasonal Hindcast Experiments

The purpose of this session was to define a set of baseline and other more specialized hindcast experiments that can serve as a benchmark for the skill of current dynamical models at subseasonal time scales. The session opened with a few remarks from Ming Ji (NOAA/OGP) and David Legler (US CLIVAR). **Tsengdar Lee** (NASA headquarters) could not attend the first day but he did make some remarks about NASA's interests later on in the workshop and we include his remarks here as well.

**Ming Ji** indicated that intraseasonal prediction would be a priority in their new strategic plan. The Office of Global Programs (OGP), which has a tradition of supporting work on seasonal to interannual time scales, is now ready to expand its program to include intraseasonal time scales, with the focus on improving services and enhancing forecast products. In particular, this is viewed as an important step in the National Weather Service's goal of obtaining a seamless suite of guidance from weather to intraseasonal to interannual time scales. It is recognized that the intraseasonal time scales represent a major gap that must be addressed in order to meet this goal.

**David Legler** indicated that while US CLIVAR is largely focused on variability on seasonal and longer time scales, there is nevertheless much interest by CLIVAR in the outcome of this workshop. The monsoon program, in particular, is very much interested in intraseasonal time scales (e.g. the MJO) for making progress on the monsoon prediction problem. There is general interest in improving our understanding of these time scales, improving model parameterizations (with emphasis on coupled aspects), and documenting the weaknesses in current models. CLIVAR therefore has much interest in the current effort to baseline the models, and to ascertain the observational requirements for making progress on this problem. David also mentioned the possibility of leveraging off the Climate Process Teams (CPTs) and the National Reanalysis effort as a way to accelerate progress on producing better parameterizations (e.g. convection schemes).

**Tsengdar Lee** cited two recent events that may have potentially important and beneficial impacts on the climate and weather research communities. The first of these was the meeting of a high end computing revitalization task force organized by OSTP to determine how to better meet the computing needs of the climate and weather communities. The second event was a speech by the president at the G8 summit meeting, in which he talked about Earth observation needs. The outcome of that speech was the planning for a 30-nation summit meeting on Earth Observations. Tsengdar also stressed that we need to clearly define our requirements for earth observations (e.g. soil moisture, altimetry, SST, etc). NASA is very much focused on the use of satellite data to advance the science, and our challenge is to clarify what kind of data we need to make progress (e.g. to improve our models, the representation of processes, phenomena, etc.). Finally, he emphasized that in developing a research plan we need to be very clear on the potential impact of this research over the next 5 to 10 years.

**Siegfried Schubert** reviewed the motivation and goals of the workshop. He emphasized that this is a planning meeting meant to make progress on implementing the recommendations of the previous workshop (Schubert et al. 2002). The first day will be devoted to addressing the recommendation that "a coordinated and systematic analysis of current subseasonal forecast skill be conducted". The second day will focus on recommendations centered on the MJO, with the morning of the second day devoted to facilitating model development efforts aimed at improving the simulation of MJO, and the afternoon session focused on continued planning for a coordinated multi-nation/multi-model experimental prediction program focused on the MJO.

## **Proposal for baseline AGCM hindcasts – morning session**

The session to define the baseline set of experiments was chaired by **Shukla**. He began by putting this effort in the context of weather and seasonal prediction. He emphasized that this was an important component of a seamless prediction problem (from daily to weekly to seasonal and longer), and that there is still much predictability that is unrealized by current models. He noted that memory in the initial conditions is still not fully explored, and that much more can be gained from boundary conditions (e.g. soil wetness, snow, and sea ice). He also noted that we need to address the continuum of interactions including for example the impact of weather on the MJO, the impact of the MJO on ENSO, and so on.

### **A strawman proposal**

In order to facilitate the discussion, Shukla next outlined a strawman proposal for the baseline set of experiments. The baseline was developed prior to the workshop by the organizing committee. The strawman proposal was the following:

Time Period: 1982-2002

Frequency: 1/month

Length: 90 days

Starting times: First of the month at 00Z

Ensemble size: 10

Atmospheric Initial Conditions:

Base state- reanalyses (NCEP/NCAR I, II, ERA)

Perturbations - breeding (TBD)

Land Initial Conditions: off-line calculation TBD

SST/sea ice:

5 ensemble members with weekly Reynolds

5 ensemble members with forecast SST (TBD)

Total Computing:

12 X 3months X 10 members X 21 years = 630 years

The idea was to carry this out in three phases with the first phase consisting of 45-day integrations for the first 5 ensemble members with the observed SST. The next 5 ensemble members with forecast SSTs would be done as part of the second phases, and finally the third phase would extend the integrations to 90 days.

The strawman proposal generated considerable discussion that pointed to a number of weaknesses in the proposed experimental design. The required computational resources made it clear this set of experiments could only be done by a few of the major centers. Scientifically, the infrequent nature of the runs (once per month) was viewed as a major flaw that would not allow adequate sampling of the various major modes of subseasonal variability (e.g. the MJO, more on that below). The question of the role of the stratosphere (up to 60 days memory) was also brought up as restricting the number of models that could adequately assess that aspect of subseasonal prediction. Other immediate responses to the strawman proposal were questions about whether we should initialize vegetation, how to handle ozone, atmosphere-ocean coupling associated with the MJO, and whether we should try to flux correct the land models. Many of the above issues were addressed during the course of the mornings discussions as outlined below. It was also emphasized that the idea for this set of experiments was to define a baseline. The afternoon's session is devoted to defining additional experiments that would address some of the above issues (e.g. impact of stratospheric data such as reanalyses, impact of ocean feedback using for example a mixed layer model, impact of improved tropical initialization using reanalyses that include precipitation assimilation, impact of initializing vegetation, etc).

## Atmospheric initial conditions

**Jeff Whitaker** discussed the possibility of using bred modes to generate the atmospheric perturbations. His experience based on the analysis of a large number of hindcasts generated at CDC (using the MRF at T62 resolution to generate bred modes for every day using the NCEP breeding method) suggests that after the first 5 days the details about the perturbations may not be that important. He suggested that we focus more on understanding and estimating the uncertainties tied to model errors and boundary conditions. Another issue that was brought up was whether we should focus more on perturbing the slow modes (e.g. MJO, annular modes, etc). Other issues considered were whether we need to worry about model spin-up when using analyses that were not generated by the forecast model. NASA has some experience suggesting that anomaly initialization may work well. It was noted that anomaly initialization may also have problems. The example was given of having a model with large systematic errors (easterly bias) in tropical surface winds that could lead to a suppression of the MJO. It was also noted that we have at our disposal several different reanalyses that could be used to generate the initial perturbations. **Grant Branstator** suggested that we clarify what we hope to get out of the experiments. For example, if the idea is to quantify the state-dependence of error growth then we don't want to perturb both the atmosphere and the boundary conditions. He also suggested that we should look to the CDC results to help choose cases to run.

## Land initial conditions

**Paul Dirmeyer** discussed several issues involved with initializing the soil from observations. He noted that soil moisture has most of its memory on 1 to 2 month time scales (the same with snow), so that the soil is potentially an important source of predictability on subseasonal time scales. The idea for initializing the various models is that we want all models to feel the same anomalies, but in a way that is consistent with each model's soil moisture climatology and variability. A major problem is that there are very few observations (especially ones that are global and continuous). Several of the available global soil moisture data sets are model-generated by forcing an off-line land surface model with various observation-based forcing fields (e.g. the Global Land Data Assimilation System or LDAS). One approach would be to have everyone use the same model-generated product but we would still have to deal with the consistency issue since one can't simply take soil moisture from one model and put in another.

Paul outlined three possibilities for generating land initial conditions. These consist of 1) having each group put their own models in an LDAS to generate consistent land conditions (e.g. the Global Soil Wetness Project - GSWP products), 2) carrying out a "poor man's" LDAS: this consists of running AMIP-style integrations but where the model precipitation falling on the land is replaced with observed precipitation (the same could be done for other forcing fields), or 3) generating some type of composite observed soil wetness product, and adding the appropriately scaled soil wetness anomalies to the annual cycle for each model. The same can be done for snow cover data sets.

## Discussion on experimental design of baseline

The following presents some of the discussion that led to various modifications to the strawman proposal (see above) aimed at making the runs more useful for assessing current prediction capabilities on subseasonal time scales.

It was argued that spacing the runs to start once per month over 20 years did not sufficiently sample all the phases of the MJO (including the seasonal dependence). **Duane Waliser** showed some results of his analysis of observations that suggested once/month sampling over 10 years could provide just enough sampling of the different phases of the MJO (though there was some question about the sampling for the different seasons). It was suggested that we should do more frequent and shorter runs (e.g. every 5 days,

and forecast length of 1 month). It was also noted that the diurnal cycle can play an important role especially over the continents in summer, so we should make sure that the output from the runs resolves the diurnal cycle. There was also some concern that with only 20 years we would not have enough cases to sample the various large-scale conditions that might affect predictability (e.g. ENSO versus non-ENSO, etc) and so we should try to extend the runs back into the 1960s.

There was considerable discussion about whether we are doing anything different from what has already been done in previous Seasonal-to Interannual (SI) projects such as with, the Dynamical Seasonal Prediction Project (DSP) and more recently the Seasonal Model Intercomparison Project (SMIP). It was argued that we already have a baseline from SMIP. On the other hand, it was noted that there are many unique aspects of the current plans including more attention to soil moisture initial conditions, the SSTs, the atmospheric initial conditions, and with greater sampling in time. It was argued that we need to view this much more as an extension of Numerical Weather Prediction (NWP) and work towards the goal of a seamless forecast product. This implies that we should run at the highest resolution possible (to further distinguish this from the SI problem). It was also suggested that we might consider truncating the forecasts for the longer lead times (as now done for NWP), but further discussions suggested that the introduction of possible temporal inhomogeneities made it less than ideal for these longer “climate” forecasts. It was further noted that increased vertical resolution may be more important than increased horizontal resolution.

Several candidate model-generated soil moisture datasets were identified. One product is a GSWP product (at COLA) that is available for the period 1979 – present. Another product was generated at NCEP (by **H. van den Dool**) and is available for the period 1948- present. The “reanalysis II” soil moisture was forced with observed precipitation and is available for the period 1979-present. The GLDAS project at Goddard has a soil moisture product for the period 1979-1993. Many of the model-generated products also include snow information. It was questioned whether we should include vegetation anomalies in the initial conditions. Some work by **Randy Koster** suggests that the impact of realistic vegetation anomalies (based on NDVI) may be small.

The question of the availability of sea ice thickness observations was brought up. It was suggested to check with the Joint Ice Center. It was noted that previous research suggests that the impact of sea ice may be primarily local. The Reynolds SST product does have a good sea ice distribution. It was further suggested that **Robert Grumbine** from NCEP may be able to answer most of our sea ice dataset questions.

The need to initialize and evolve ozone was also discussed. It was noted that NCEP produces ozone products in their GDAS – now have 8 years available. The NCEP/NCAR reanalysis does not include an ozone product, though ERA40 does have an online ozone product.

## On the choice of the SST

There was considerable discussion on the choice of SSTs (for example should they be observed or predicted?). The strawman proposal called for including both. In either case, it was noted (see Section II B) that SST specification is a problem for predicting the MJO. AMIP (with weekly SST) and interactive runs show that there is about a 10-day phase difference associated with the relative lag between convection and SST anomalies for the forced versus interactive case – this would presumably have serious consequences for predictions on subseasonal time scales. This highlighted the need for mixed layer experiments and fully coupled runs (subject of afternoon session). In the latter case there are initialization problems that may make it difficult to beat persistence for the first two months. It was questioned whether we have a basis for predicting subseasonal SST variations. It was noted that NCEP will soon have results available for study from an ocean data assimilation experiment available for the

period 1982 to the present (output every 5 days). The daily atmospheric forcing used in that experiment is from reanalysis II.

**Huug van den Dool** reviewed some of the possible choices for predicting the SST at subseasonal time scales. These consist of:

- 1) The two-tiered approach (off-line SST product either from coupled or statistical model)
- 2) Running a fully coupled system
- 3) Damping (in some way) the initial SST anomaly – difficulties in case of growing SSTs

At NCEP they currently have a constructed analogue method applicable for seasonal means. They are now testing the method for the subseasonal problem (pentad forecasts out to 2 months). The basic issue is whether atmosphere-ocean interaction is important? In some ways prescribed SSTs may do harm (e.g. the case of the MJO described earlier; see also Section II B). It is also unclear whether there is any skill in pentad forecasts of SST out to 2 months. As mentioned earlier, coupled models have initialization problems. Statistical methods also have problems – for example, the loss of details associated with not keeping enough EOFs.

## Additional experiments – afternoon session

The afternoon session was devoted to defining additional experiments that could serve to complement the baseline experiments discussed in the morning session by providing additional information on sensitivity to initial conditions, the impact of SST feedbacks, the role of the stratosphere, etc. The session was chaired by **Eugenia Kalnay**. Eugenia noted that the first topic in the agenda (using reanalysis products to initialize the runs) had already been addressed in the morning session.

The session began with a talk by **Arthur Hou** on his work on precipitation assimilation. Arthur emphasized that the impact of assimilating TRMM precipitation is to not only improve the precipitation in the assimilation but also related quantities such as clouds and radiative fluxes. He noted that the use of Incremental Analysis Updates (IAU) eliminates the shocks and spin-up that normally occur as a result of data insertion. The IAU also appears to help the wind field adjust to the precipitation information – this is different from the experience of some other efforts where the model quickly loses memory of the precipitation. Eugenia emphasized the need to use precipitation information to change potential vorticity – not just parameters in a column. Max Suarez noted that the precipitation/wind adjustment problem may be more relevant to the middle latitudes than in the tropics, where the errors are presumably primarily in the divergent wind field due to incorrect heating. Max questioned how relevant precipitation assimilation is to the initialization of the MJO. Arthur replied that the relevant experiments are yet to be done – presumably as part of this project. Hua-Lu Pan noted that NCEP also finds improvement to the tropical analysis from precipitation assimilation, though the focus of the forecast results so far has been on the short and medium range. It was also noted by Matt Newman that some work at the Climate Diagnostics Center (CDC) using chi-adjusted heating to correct (improve) the divergent wind fields in reanalyses showed substantial case-to-case variability in the impact so that it is likely that a large number of cases will be needed to adequately assess the impact.

**Kingtse Mo** noted that there is still a lot of work to be done to improve model physical parameterizations. She pointed out that the ability to test local processes should be much improved as a result of the enhanced observations that will become available in the summer of 2004 as part of the North American Monsoon Experiment (NAME) observational program. The use of NAME observations could serve as an important component of the “additional runs” to be considered for the subseasonal hindcast experiments.

**Randy Koster** described an experiment (Global Land-Atmosphere Coupling Experiment - GLACE) that is attempting to characterize how strong the land is coupled to the atmosphere in different models. The

experiment is already underway, though he indicated that there is still time to participate. The experiment consists of a Control run in which all land prognostic fields are saved at every time step. An ensemble of runs are then made in which at each GCM time step all land quantities are replaced by the saved quantities from the control run. In that way all ensemble members “see” the same land conditions. If all the ensemble members look the same this would indicate that the model has strong land control/coupling. If, on the other hand, all the ensemble members are very different this would indicate very weak coupling. Previous pilot experiments suggest that there are large differences between models in the strength of the coupling. Unfortunately there are no data to verify which model is performing correctly. The current experiments update both temperature and soil moisture at every times step. Separate experiments will be done where just the soil moisture is updated. All the results should be processed by the end of year. The entire set of experiments should produce a total of about 12 years of integration per model. Max Suarez asked about how the memory inherent in the land compares with the memory from coupling. Randy indicated that GLACE will also address that issue. Further information can be found at the web site <http://glace.gsfc.nasa.gov>

**Malaquias Pena Mendez** summarized the results of an observational analysis to assess the impact of the ocean on subseasonal anomalies. The idea is to determine what would be the impact of prescribing SST and ignoring the feedbacks. The questions he addressed included: Can we quantify the feedback? Are AMIP runs applicable to the extratropics? He found that there are more longer-lasting anomalies in the tropics compared with extratropics. Most long lasting anomalies are locally coupled to SST. He characterized the anomalies as either cyclonic over warm indicating ocean driving, or cyclonic over cold indicating atmospheric driving. When looking at 15-day and longer anomalies, he found that atmosphere driving prevails in the extratropics, while ocean driving prevails in the tropics (similar to previous studies). Those were considered to have normal coupling. He also found instances of abnormal coupling (reverse phase), but they tend to be short lived. He found that AMIP runs tend to kill the anomalies faster than observed in extratropics, and extend the anomalies longer than observed in tropics. The results show we need to have feedback from the atmosphere to the ocean so that AMIP is not an optimal strategy (does not give an upper limit). Bill Lau noted that there must also be some ocean feedback in the extratropics to get long lasting atmospheric anomalies. Matt Newman asked whether the results take into account the atmospheric bridge.

**Hua-Lu Pan** summarized some recent results from the NCEP atmospheric and coupled models. He noted that NCEP has a history of making seasonal models out of the medium range forecast model – he noted further that it takes lots of work. The current effort started 3 years ago. The focus is on the need for a seamless strategy to predict weather, seasonal, and now subseasonal time scales. He noted that the current model run at T62 and with 64 layers seems to produce reasonable statistics of easterly waves. He further showed that the model appears to get MJO – like behavior (40-50 day signals). Thirty day hindcasts during MJO events using observed SST damped to climatology seemed to produce the correct change in amplitude but not propagation. Further runs with observed SST produced a somewhat better signal. Current efforts are focused on coupled runs with the GFS 2002. He noted that the version with 28 vertical layers in the atmosphere produced too cold SSTs and didn't produce a realistic ENSO. However, with 64 vertical layers in the atmosphere, the coupled model produced improved SST anomalies and more realistic El Nino variability. It is still an open question about whether we can predict the MJO. There is evidence for MJO signals in the long runs: during El Nino these are more stationary. Hua-Lu pointed out that they need to do more runs and more analysis, and welcome collaboration on this effort. It was noted that the increase in vertical resolution was uniform so that most of the increased layers were in the stratosphere. Suru stated that the MJO seems to have better phase in the coupled run compared with AMIP run.

**Frederic Vitart** presented an analysis of the impact of coupling on the bias in the ECMWF monthly forecast system. The basic coupled system, described by Frederic at last year's workshop, includes a T159, 40 vertical layer-version of the operational weather prediction model. Thirty-day integrations are

run every 2 weeks. Five-member ensemble hindcasts have been produced every two weeks for the 12-year period 1990-2001, in order to estimate model bias and correct (a posteriori) the real time forecasts. The coupled hindcasts were compared to another more limited set of hindcasts in which the SSTs are specified from the observations. The results showed that the SST drift is characterized by a warm bias in the eastern Pacific that grows linearly in time. The surface temperature in the extratropics showed a cold bias, similar to that seen at the medium range. In general the impact of coupling on the surface temperature bias is small. The impact of coupling on the u and T at 850mb bias was also small with the week 1 bias very similar in structure to the week 4 bias in both sets of runs. The precipitation bias showed more differences in the two sets of runs, with the coupled model week 4 bias in the eastern Pacific reflecting the warm bias in that region.. The basic conclusion was that on subseasonal time scales the bias in the coupled and uncoupled runs is quite similar. Furthermore, the basic spatial structure of the bias at four weeks is very similar to that already seen at the medium range. For seasonal time scales (month 3) the coupling bias is greater compared with the uncoupled runs. An analysis of the bias in blocking events showed that the bias is evident in both sets of runs– suggesting the deficiencies must be associated with the atmospheric model.

**Bill Lau** described the development and initial results from a mixed layer ocean model coupled to an atmospheric model. He emphasized that this is an important tool for understanding air-sea interaction. As motivation for the model development, he showed some results from a study of summer time atmospheric anomalies across the Pacific. The results suggested that North Pacific air-sea interaction may be important for maintaining the anomalies. He discussed the importance of the qflux correction term to maintain a realistic climate. He also outlined several different experiments that could be done with different regions of specified SST and mixed layer ocean (e.g. a mixed layer tropical ocean to study MJO or specified tropical SST and mixed layer ocean in the middle latitudes). Bill indicated that they still need to look at intraseasonal variability in the model. Matt Newman stated that he did something similar with the GFDL model and that that model did reproduce the observed variability.

**Ming Cai** described a set of experiments that he called “coupled AMIP” runs, in which the model is integrated for a short time (say every other day) forced by observed SST. In the short integrations the atmosphere remains synchronized with ocean. One can then look at all 2-day forecasts, 5-day forecasts, and so on, to assess the drift. Instead of specifying the SST, the surface fluxes forcing the atmosphere could be obtained from an ocean reanalysis.

**Huug van den Dool** discussed the need for statistical methods. They can be used to:

- 1) Serve as a control method – what is achieved by the dynamical models?
- 2) Help understand the dynamical model results
- 3) Help to determine the simplest method for achieving the results

He noted that one should distinguish between diagnostic and forecasting applications. The dynamical models may be more useful for diagnosing the results and may not be as useful for forecasting. He listed several popular statistical forecasting methods including Canonical Correlation Analysis (CCA), Optimal Climate Normals (OCN), constructed analogues, and composites based on major recurring events such as EL Nino. He noted that empirical methods have also been applied to model output. This includes a CCA done by Jeff Anderson, and the CCA of a large ensemble of AMIP runs done by Marty Hoerling. Another method, called Empirical Wave Propagation, has proven useful for diagnosing for example the MJO phase speed.

Huug stressed the importance of knowing how many degrees of freedom (df) in which we have forecast skill. This is relevant to understanding why simple models do as well or better than physical models. He postulated that:

- 1) all empirical methods are basically linear

- 2) physical models are better at nonlinear terms
- 3) a physical model needs at least 3 df to be functionally nonlinear
- 4) for the seasonal forecast problem, physical models have less than 3 df (the models are functionally linear with random noise from nonlinear terms)
- 5) empirical methods can cover about 3 df using 50 years of data

It follows that physical models must have more than 3 df to be functionally better than linear methods. In contrast, numerical weather prediction (NWP) models have many df so that empirical methods can't compete. He further suggested that current seasonal coupled models have skill in approximately 1 df. It is unclear how many degrees of freedom we have in forecast skill at subseasonal time scales, though the indications are that there are more than for the seasonal problem associated with, for example, soil moisture, SSTs, the stratosphere, trends, the MJO, and other low frequency modes of variability. It was pointed out that we also need to consider higher moments, and more general seasonal changes in probability density function (PDF) of weather. This would suggest that there are potentially more df than suggested above, though that would only be true if such changes are the results of more than just shifts in the seasonal mean. Huug indicated that developing methods for estimating the df in forecast skill should not be difficult, but the methods have not yet been developed.

Huug also briefly discussed post processing of forecasts. He emphasized that systematic errors are not the same as time mean errors. There are typically very large error bars on the time mean. Ideally one should create large samples by reforecasting (e.g. the work by Jeff Whitaker et al at CDC, and Jae Schemm at NCEP). Corrections for bias in both the mean and variance and more generally the full PDF can substantially improve probability forecasts. The corrections should also be stratified by season. Huug also noted that in many cases, large systematic errors don't seem to hurt the forecast in the sense that one can remove the systematic error after the fact (there does not seem to be a correlation between skill and the size of the systematic errors)– this suggests linearity.

**Matt Newman's** talk focused on using a Linear Inverse Model (LIM) to diagnose the results of a full AGCM. The LIM Matt discussed consists of 26 components based on weekly variability in stream function (250mb and 750mb) and heating. The imposed LIM noise is assumed to be state independent. The LIM shows skill at week 2 and 3 that is comparable to the MRF AGCM. This allows one to diagnose the AGCM skill with the LIM. For example, one can assess the sensitivity to heating for a particular target anomaly. One can also look for the fastest growing disturbance for a particular forecast lead time (these are also the most predictable disturbances). One can determine where the greatest sensitivity is to heating. This may be different in models and observations. Predictability can be assessed by computing the signal to noise ratio in the LIM. One can further look, for example, at the separate contributions from extratropical interactions and heating to predictability. The LIM can also be used to predict skill. It is also instructive to try to isolate those instances where the AGCM does worse than expected based on the LIM results. Future work by Matt involves combining the LIM with the inverse modeling being done by Cecile Penland that focuses on predicting SSTs.

**Jeff Whitaker** discussed the results of post-processing that he carried out on the suite of 15-day reforecasts that were done for every day of the period 1979 – present, using the 1998 MRF. He posed the question - why should we expect to produce better forecasts of the PDF as a result of post-processing? He indicated that systematic errors can shift the PDF, and the shift can be comparable in magnitude to the predictable signal in the mean. He also noted that the ensemble spread in the forecasts is always too small because we don't adequately sample all sources of uncertainty. The basic point is that we must correct for bias in the estimates of both the first and second moment statistics. Realistic spread in the ensemble is needed to produce reliable forecasts (e.g. too small spread makes the model overly confident). The forecasts also need to be sufficiently “sharp” to be useful –we want high “resolution” in the sense that we want more than just the climatological probabilities of 1/3,1/3,1/3. Jeff examined how many years of data are really required to do the post-processing. Do we need the full 23 years of daily reforecasts? He

presented some analysis that suggests that carrying out forecasts every 5 days over 20 years should be adequate. It was not clear how many ensemble members are required.

**Jim Kinter** presented an overview of the GrADS/DODS Server (GDS). He highlighted that depending on decisions made regarding resolution, the number of cases, the number of ensemble members, the forecast length, the number of participating models, and the number of variables saved, the data volume from this project could range anywhere from 10 Terabytes to a Petabyte. The GDS allows desktop analysis of the data distributed around the country. The GDS allows comparing multiple datasets via the internet (distributed data analysis). The GDS supports multiple data formats and data subsetting. The data need to be made public (put outside the firewall) and the server must have the software that allows subsetting. There is also now the capability to do analysis remotely, on the server side. This allows doing all the data reduction on the server side and then just bringing back the results for visualization. COLA scientists are now using GDS at NCAR to very efficiently analyze results of their model runs.

### **Final recommendations for baseline experiments:**

The following are the agreed-upon characteristics of the baseline set of hindcast experiments designed to assess the skill of subseasonal predictions with current AGCMs. The experiments need to 1) be clearly distinguished from previous and ongoing seasonal forecasting projects, 2) be useful to the operational centers, 3) contribute to MJO development, and 4) serve as a baseline for the experimental prediction program (C- below). The characteristics of the initial phase of the experiments are:

**Time period:** most recent time period (1992 – present)

**Forecast length:** 45 days

**Forecast frequency:** every 5 days – 73/year

**SST:** TBD – but most likely damped persistence (no “cheating”)

**Ensemble size:** minimum of 10

**Perturbations:** TBD – but should include analyses from different centers if feasible

**Resolution:** high as possible

**Land initial conditions:** TBD – currently assessing different soil moisture products

**Total Computing:** 73 X 3 months X 10 members X 10 years ~ 2400 years

A number of additional experiments were discussed that could serve to assess sensitivities to initial conditions and boundary forcing. These include prediction experiments that use a mixed layer ocean, and experiments to assess the impact of analyses that include precipitation assimilation. Other experiments could be done to assess sensitivity to model formulation, especially experiments designed to examine the impact of model parameters that affect the representation of the MJO.

## **B. MJO Modeling & Simulation: Rectifying Shortcomings**

This session was opened by **Duane Waliser** who made the following remarks in an effort to motivate the session’s objectives.

**Fact 1:** The MJO is the most dominant form of intraseasonal variability in the tropics. In terms of rainfall generation, the most dominant forms anywhere.

**Fact 2:** The MJO has very significant and important influences on local tropical weather variations and the evolution of the active and break periods of the Asian/Australian Summer monsoons.

**Fact 3:** The MJO has modest influences on mid-latitude weather variability and its extremes as well as on tropical cyclone development.

**Fact 4:** The MJO can in some cases influence the evolution of ENSO variability via its influence on the ocean equatorial waveguide.

**Conclusion 1:** The MJO is an important mode of weather/climate variability that must be simulated in our GCMs with as great of fidelity as possible to afford realistic representation of the above processes in our weather/climate simulations.

**Fact 5:** Realistic representation of the MJO is imperative in order to fully realize the potential of medium- to extended-range weather forecasts; certainly in the Tropics and very likely in the mid-latitudes.

**Fact 6:** Realistic representation of the MJO is imperative in order to fully realize the potential of short-term/seasonal climate forecasts. At a minimum, this representation is important to properly assess the uncertainty of such forecasts. At a maximum, this will be fundamental to improve skill in the deterministic component.

**Conclusion 2:** Quantitative gains in the skill and the assessment of uncertainty of our weather and short-term climate forecasting can be made by improving the representation of the MJO in our weather/climate forecasting models.

**Fact 7:** Achieving realistic representation of the MJO in our atmospheric and ocean-atmosphere coupled GCMs has not readily forthcoming; in fact it has been illusive.

**Fact 8:** Significant effort has been put forth by a number of individual model developers/groups to improve the representation of the MJO in their GCMs - to some modest avail on rare occasions.

**Fact 9:** A concerted effort by a number of agencies, modeling groups, or individuals have yet to take place to rectify MJO shortcomings in our GCMS.

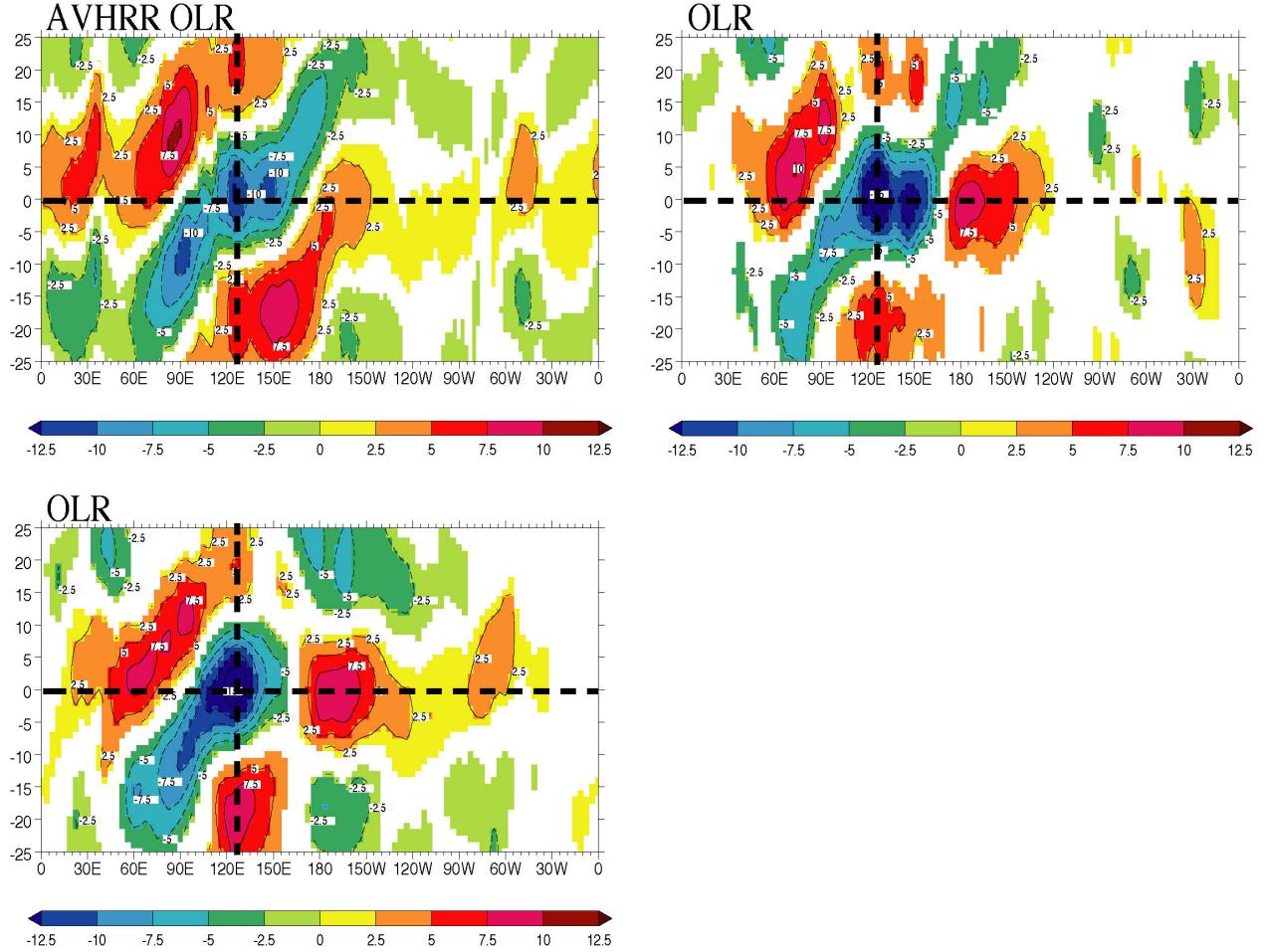
#### Questions:

- Would such a concerted effort be a worthy effort to undertake?
- What would the framework of this effort be and/or include (e.g., working group, call for proposals, a suite of well-designed experiments, additional field work)?
- What are the initial steps that need to take place in order to put this into motion?

The above remarks were followed by two brief presentations meant to highlight the known and typical systematic errors associated with GCM representations of the MJO. The first was by **Ken Sperber**, who provided an assessment based mainly on the MJO variability that is most common during northern hemisphere winter (in this case, Nov-Mar). This presentation included an evaluation of the AMIP II diagnosis of the MJO, some corresponding analysis for a set of coupled GCMs, a comparison of these results to the AMIP I study (Slingo et al. 1996), and an examination of the relationship between the mean state errors of the model and the errors associated with the MJO. The assessment involved 19 AMIP II models and 4 coupled GCMs with observational data composed of NCEP/NCAR reanalysis, OLR and CMAP rainfall data. The analysis was based on first identifying winters that exhibited strong MJO variability via the interannual variability in the variance of the 200 hPa tropical zonal mean zonal wind (Sperber 2003). From these winters, EOF analysis of the bandpassed (20-100 day) OLR was performed to isolate the spatial-temporal evolution of the MJO, namely by keeping and examining the first two modes. As a means to evaluate the models, their bandpassed OLR was projected onto the observed modes (cf. Duffy et al. 2003). The resulting principal component time series (i.e. PC-1 and PC-2) were then analyzed in terms of their variance and lagged correlation values (**Table 1**). The main conclusion from this part of the analysis is that the models (still) fail to represent a dominant and coherent mode of intraseasonal variability within the large-scale tropical circulation. This is exhibited by the considerably smaller values of PC-1 and PC-2 for nearly all the models and the models' weaker correlation between values of PC-1 and PC-2. However, it should be noted that within a given pair of CGCM and corresponding AGCM models, ocean-atmosphere coupling leads to an improved lead/lag structure of the MJO either through an enhanced amplitude of PC-1/PC-2 and/or a greater lagged correlation value. Analysis of the mean states in conjunction with the models' representations of the MJO showed that the

Model	PC-1	PC-2	R	Lag (days) PC-2 leads PC-1 (positive)
AVHRR	211.3	205.6	0.67	12
CCCMA-99a	100.3	107.0	0.26	11
CCSR-98a	106.4	91.7	0.30	13
CNRM-00a	155.1	143.3	0.42	14
COLA-00a	100.5	85.7	0.16	26
DNM-98a	63.0	67.1	0.16	25
ECMWF-98a	102.5	97.5	0.20	-11
ECMWF-98b	121.8	105.7	0.29	-13
GFDL/DERF-98a	159.0	182.1	0.36	12
GISS-98a	64.0	54.6	0.23	-7
GISS-02a	37.1	37.1	0.17	-15
HADAM2 (AMIP I; 1979/ 80-1987/88)	166.5	130.9	0.40	18
HADAM3 (L58) (UGAMP-98a)	117.1	102.8	0.28	14
JMA-98a	165.3	155.3	0.29	10
MPI-98a (ECHAM4)	222.2	215.8	0.35	12
MRI-98a	174.2	164.1	0.31	9
NCAR-98a (CCM3)	91.9	100.2	0.18	10
NCAR-02a (CAM2)	95.3	95.8	0.19	-24
NCEP-99a	108.9	108.6	0.24	12
NCEP-99b	104.1	98.4	0.22	24
HADCM3 (L30)	104.4	96.0	0.45	8
IAP/LASG GOALS	123.8	129.2	0.42	9
NCAR CCSM2	91.5	115.9	0.28	20
SINTEX (ECHAM4/OPA8.1)	231.2	201.5	0.44	12

**Table 1: Observed and simulated MJO characteristics.** The columns give the observation/model designation (the last 4 entries are from the coupled models), the standard deviations of PC-1 and PC2, the maximum positive correlation, R, between PC1 and PC-2, and the time lag at which it occurred. Positive time lags correspond to eastward propagation. Shaded entries highlight models for which an AMIP II integration and a coupled ocean-atmosphere simulation using the same atmospheric model are available.



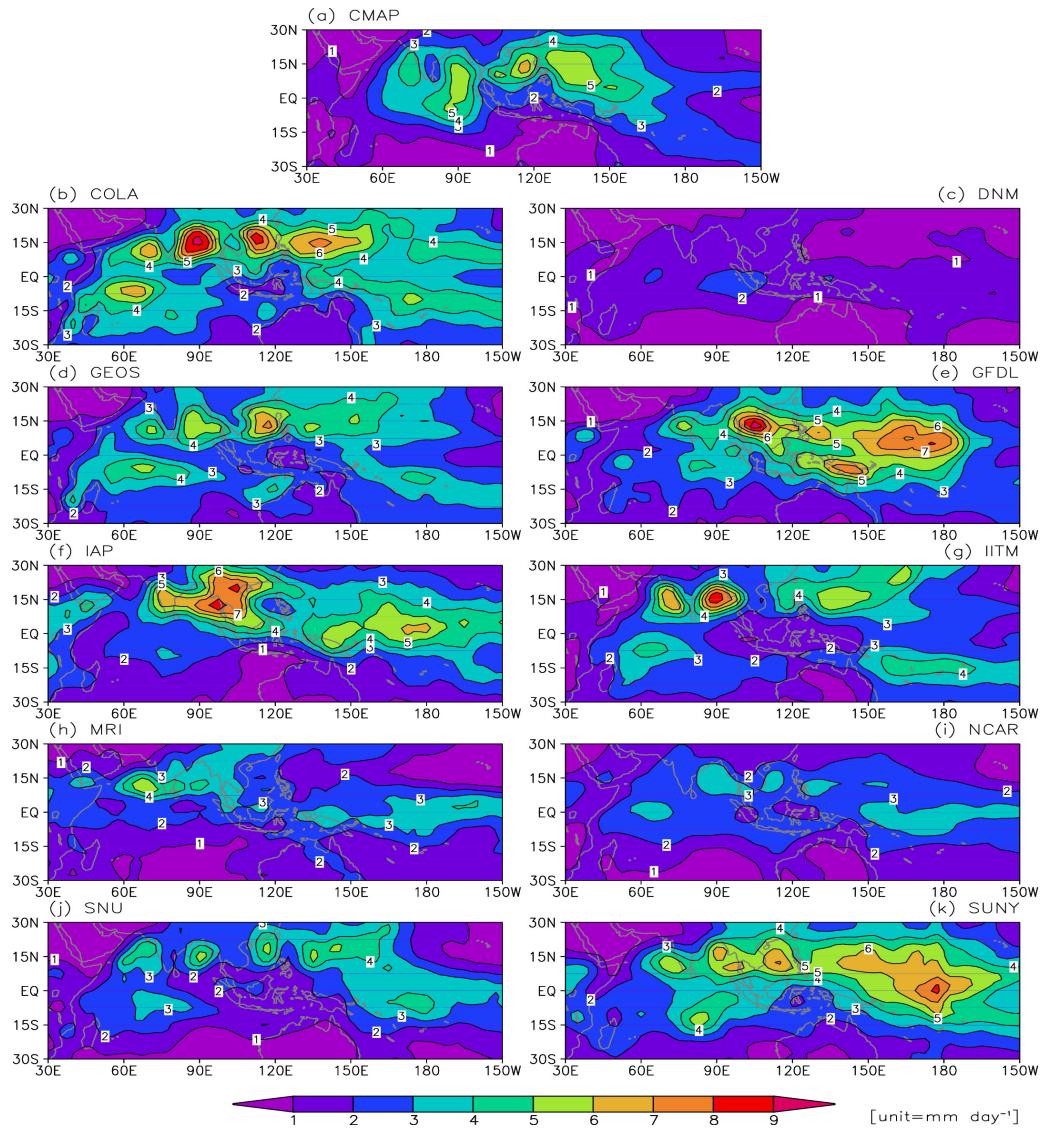
**Figure 1.** Longitude/time lag (days) plot of the regression of PC-1 (see text) with 5N-5S averaged 20-100 day bandpass filtered OLR. The data has been scaled by a one standard deviation perturbation of PC-1 to give units of  $\text{Wm}^{-2}$ . The vertical dashed line corresponds to the longitude of strongest convection at time lag zero (the horizontal dashed line). The analysis is for November-March 1979/80-1994/95 for the AVHRR OLR (upper left), the ECHAM4 AMIP integration (upper right), and for 9 winters from the ECHAM4/OPA8.1 (SINTEX) coupled integration (lower left).

propagation of convection into the western/central Pacific tends to be limited by systematic error of the lower tropospheric zonal wind. For example, **Figure 1** shows a canonical MJO pattern in terms of OLR for the observations, a particular AGCM and the model's corresponding CGCM. In this case, the MJO in the AGCM shows weak and incoherent eastward propagation relative to the observations. For the corresponding coupled version of the model, this feature is much better represented, particularly in the Indian Ocean – a region where both the CGCM and observations, but not the AGCM, exhibit low-level westerlies. These results imply that eastward propagation tends to occur (be limited) in regions of low-level westerlies (easterlies) and stresses the importance of achieving correct model mean states.

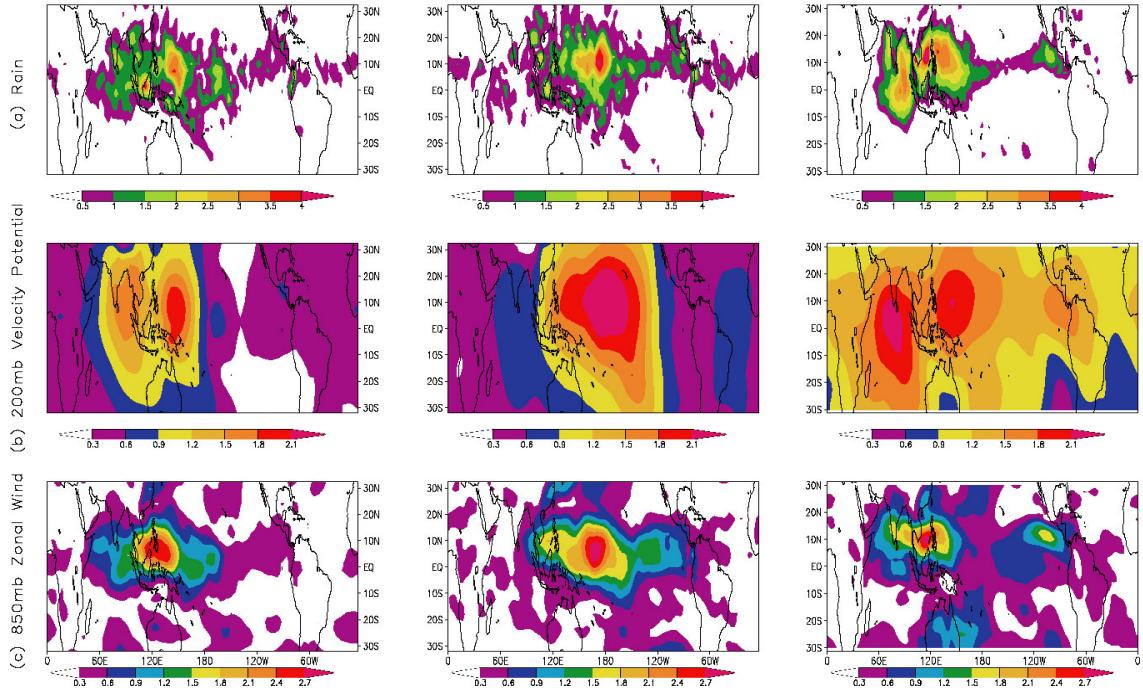
The second presentation was by **Duane Waliser** who provided an analogous examination of GCM representations of the MJO variability that is most commonly exhibited in northern hemisphere summer (in this case, May-Sep). In this case, the assessment was based on ten AGCMs that participated in the CLIVAR Asian-Australian Monsoon Model Intercomparison Project (Kang et al. 2002). Each model provided a 10-member ensemble from 9/1/96 to 8/31/98 using prescribed weekly SSTs, and an associated climatology using monthly SSTs from 1979-1998. The intraseasonal variability (ISV) was isolated via 20-90 day bandpass filtering and the analysis involved an

examination of the spatial structure of the variability, the propagation characteristics of the dominant intraseasonal mode and the implications for downstream tropical teleconnections. The main conclusions from this study include the following. 1) Several models exhibit intraseasonal variability at or above the level found in observations with spatial patterns that often resemble the observed pattern (**Figure 2**). 2) The fidelity of a model to represent boreal summer versus winter ISV appears to be strongly linked. 3) Most models' MJO patterns do exhibit some form of northeastward propagation. However, they are typically less coherent, lack sufficient eastward propagation, and have smaller zonal and meridional spatial scales, and are often limited to one side or the other of the maritime continent. 4) The most pervasive and problematic feature is that model MJO patterns lack variability in the equatorial Indian Ocean (**Figure 2**). In some cases, this appears to result due to the tendency for models to form double convergence zones and it might possibly be influenced by the lack of SST coupling. 5) The above shortcomings not only result in a poor representation of the local rainfall but also significantly influence the models' representations of the global-scale teleconnection patterns associated with the MJO (e.g., the downstream patterns that appear to influence the development of tropical storms/hurricanes).

Evidence for the importance of SST coupling in regards to the shortcoming mentioned above comes from results presented of an analysis of coupled and uncoupled versions of the GFDL GCM, in which the SSTs from the coupled simulation (i.e. CGCM) were specified as fixed values in an AGCM simulation (Zheng et al. 2003). The results of this analysis showed that the AGCM exhibited almost no ISV in the Indian Ocean during boreal summer while the CGCM on the other hand did show a considerable variability in this region (**Figure 3**). Other differences remarked on from this study are that the wavenumber-frequency spectra of the AGCM exhibited an unrealistic peak in variability at low wavenumbers (1-3, depending on the variable) and about 3 cycles/year. This unrealistic peak of variability was absent in the CGCM which otherwise tended to show good agreement with the observations. In addition, the AGCM showed a less realistic phase lag between the ISV-related convection and SST anomalies. In particular, the CGCM exhibited a near-quadrature relation between precipitation and SST anomalies, which is consistent with observations, while the phase lag was reduced in the AGCM by about 1.5 pentads (~ 1 week). This difference in phase relation (see also presentation by Wang below) has serious implications for determining how to conduct hindcast/forecast experiments at the subseasonal time scale, namely that the notion of a “perfect-SST” (i.e. specified from observations) framework is not ideal for the subseasonal problem and that coupling is a near necessity.



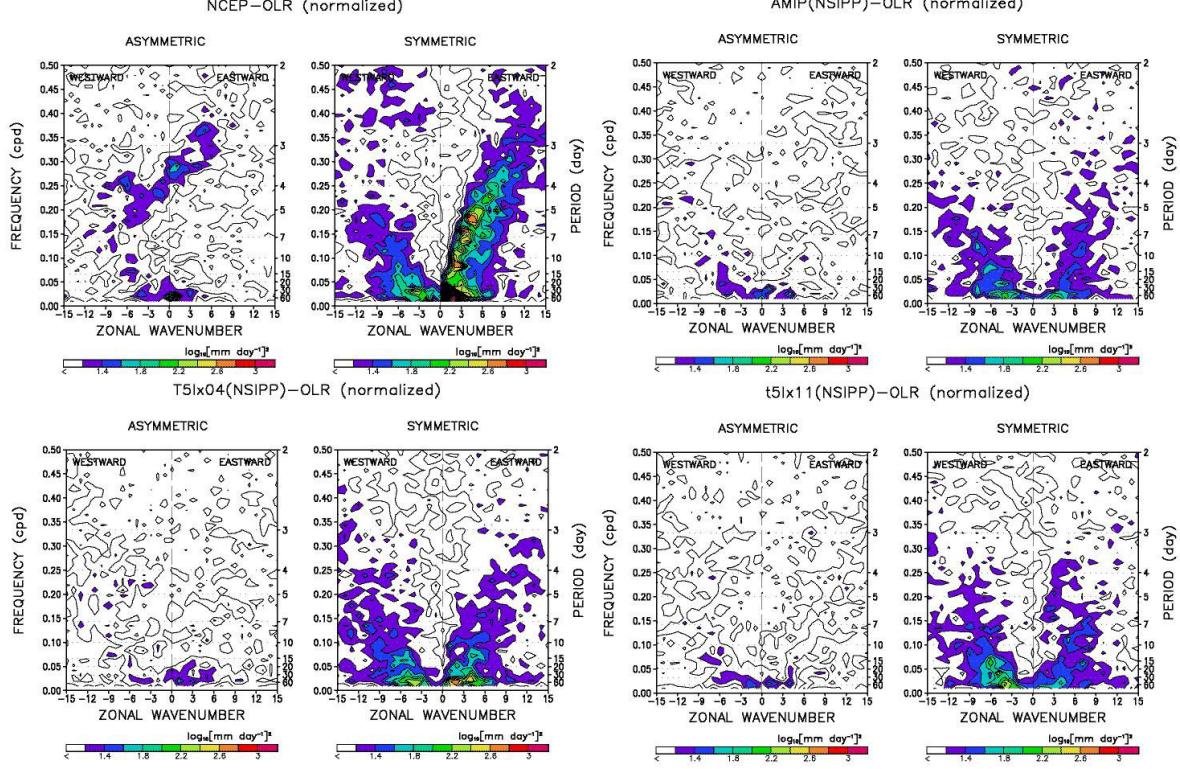
**Figure 2.** Standard deviation of 20-90 day filtered rainfall (mm/day) for Northern Hemisphere summer from the observations (top) for 1979 to 1998 and for the ten participating AGCMs (lower). In the case of the models, there were 20 summer seasons of data, i.e. ten members each consisting of two years.



**Figure 3.** Standard deviation of the Northern Hemisphere summer (May-Oct) composite MJO structure (not shown) – in terms of (top) rain rate, (middle) 200-mb velocity potential, and (bottom) 850-mb zonal wind from the CGCM (left), AGCM (middle), and observations (right). The total number of MJO events that went into the construction of the composites is shown in the title. Units: mm day<sup>-1</sup> for rain,  $1 \times 10^6$  m<sup>2</sup> s<sup>-1</sup> for the 200-mb velocity potential, and ms<sup>-1</sup> for 850-mb zonal wind.

Following the above two introductory presentations, were a number of presentations aimed at describing specific efforts by individuals or modeling groups to improve the MJO simulations and/or reporting on MJO sensitivity to various model changes. The first presentation was by **Julio Bacmeister** who provided an overview of model sensitivity experiments with the NSIPP AGCM designed to better simulate the MJO. Most notable were experiments in which limits are placed on the maximum diameter, and thus on the minimum entrainment rates, of an entraining plume within the relaxed Arakawa-Schubert (RAS) convective parameterization (Tokioka et al. 1988). In addition, other experiments involved modification of the “gustiness” parameter within the calculations of the turbulent surface heat fluxes and changes to the convective auto-conversion within the RAS scheme. The experiments were conducted at 2.0°x2.5° (latxlon) resolution and used SSTs specified from observations for the years 1995-1999. Some of the most interesting results are illustrated in **Figure 4** which shows filtered space-time Fourier analyses (Wheeler and Kiladis, 1999) of daily OLR along the equator (10°S-10°N). The OLR fluctuations are separated into anti-symmetric and symmetric modes before analysis. Results are shown from NCEP re-analysis (top-left pair), from the NSIPP-1 AGCM (top right) and from two sensitivity simulations using different minimum entrainment limits in the NSIPP-2 model;  $\lambda_{\min} \sim (600\text{m})^{-1}$  (bottom left), and  $\lambda_{\min} \sim (2000\text{m})^{-1}$  (bottom right). In general the subseasonal variability in the NSIPP models is weak compared to the re-analysis. However, the NSIPP-2 simulation with a stricter minimum entrainment limit shows a significant enhancement in power in low-frequency, symmetric OLR (MJO-type) variability. Other analyses, e.g. equatorial time-longitude plots of 200 mb, 5-60 day filtered, equatorial zonal wind anomalies (not shown) confirm that this simulation possesses more realistic looking sub-seasonal variability than the other two NSIPP AGCM simulations. Unfortunately, the stricter minimum

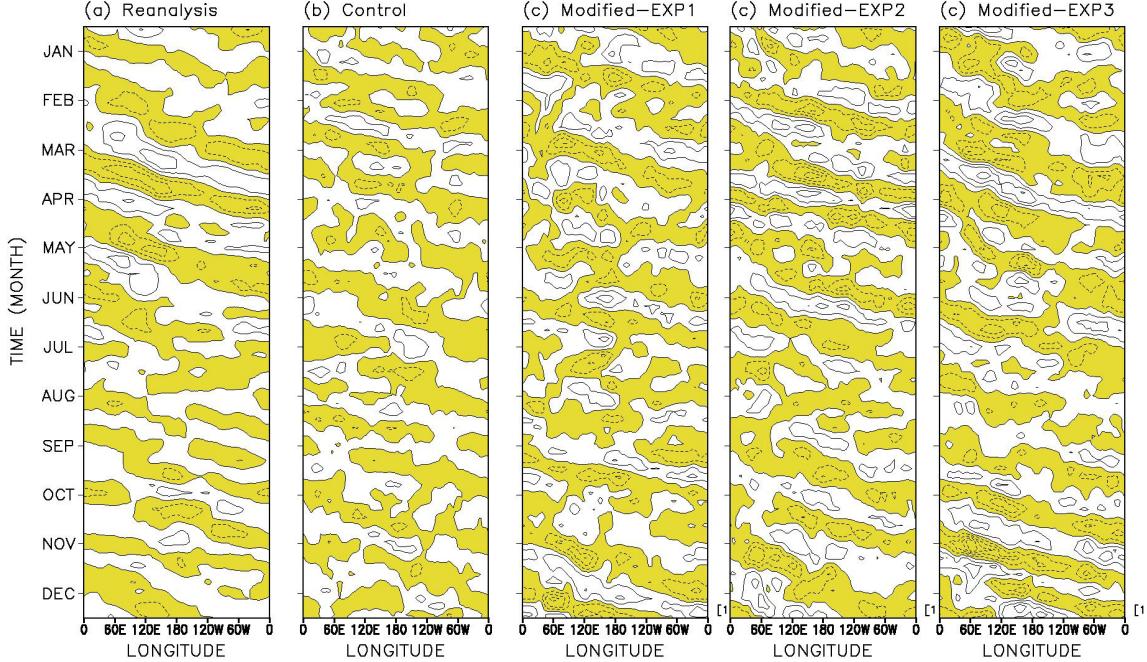
entrainment constraint also degrades the simulated mean precipitation pattern (not shown). In simulations with a strict constraint, excessive precipitation rates develop over and around the Phillipine Islands in northern summer. This precipitation error is accompanied by a spurious extension of strong low-level westerlies far into W. Pacific.



**Figure 4.** Space-time Fourier analyses of daily OLR along the equator ( $10^{\circ}\text{S}$ - $10^{\circ}\text{N}$ ). The OLR fluctuations are separated into anti-symmetric and symmetric modes before analysis. Results are shown from NCEP re-analysis (top-left pair), from the NSIPP-1 AGCM (top right) and from two sensitivity simulations using different minimum entrainment limits in the NSIPP-2 model;  $\lambda_{\min} \sim (600\text{m})^{-1}$  (bottom left), and  $\lambda_{\min} \sim (2000\text{m})^{-1}$  (bottom right).

**Myong-In Lee** presented a number of MJO sensitivity experiments with the Seoul National University (SNU) AGCM, exploring possible improvements of the MJO representation through the modification of moist convection and cloud parameterizations (**Figure 5**). Using a highly idealized aqua-planet version of the model, he showed the sensitivities to: 1) the minimum entrainment rate constraint for the deep convective plumes of the Arakawa-Schubert scheme (namely Tokioka modification; see also the above presentation by Bacmeister) and 2) the layer-cloud precipitation time scale. In the Tokioka modification, a critical value of cumulus entrainment rate (which is defined as a function of PBL depth) is introduced and only convective plumes exceeding this critical value are permitted, instead of permitting all plumes as in the original parameterization (Tokioka et al., 1988). Based on his results (Lee et al., 2001; 2003), simulated intraseasonal variability has been substantially increased by the Tokioka modification, but this is discernable only when the cloud-radiation interaction is not allowed in the model by prescribing time mean radiative fluxes. When the cloud-radiation interaction is included, the eastward propagation of large-scale waves becomes overly contaminated by small-scale westward moving transients. These small-scale transients are excited by the feedback process between cumulus anvils and the considerable diabatic heating they produce via longwave radiation. Reducing the layer-cloud precipitation time scale

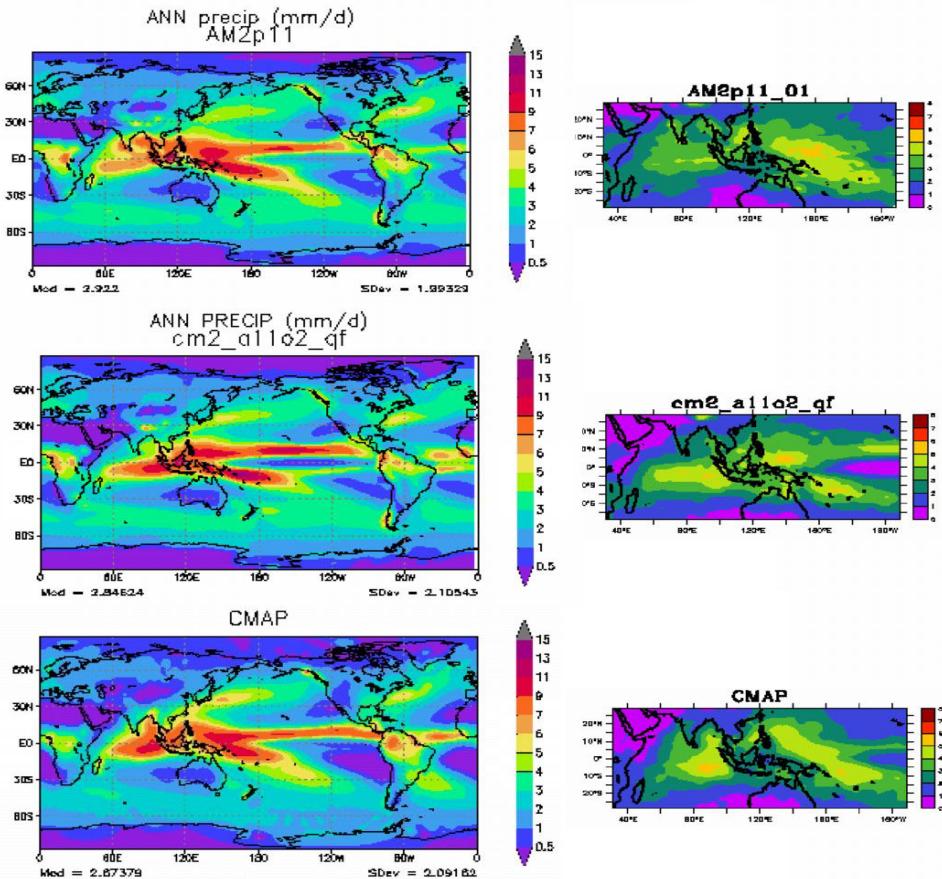
gives fast auto-conversion of cumulus anvil to the raindrops and this moderates the strong positive feedback between cumulus anvil and longwave radiation. Together with the Tokioka modification, reducing the precipitation time scale improves the large-scale wave propagation characteristics associated with the MJO variability. In addition, consistent with previous findings, coupling to an ocean mixed-layer showed increased intraseasonal variability and improved MJO propagation characteristics (e.g., Flatau et al. 1997; Waliser et al. 1999; Kembell-Cook et al. 2002).



**Figure 5.** Time-longitude diagrams of 200 hPa velocity potential ( $10^{\circ}\text{S}$ - $10^{\circ}\text{N}$ ) during 1997 obtained from (a) the NCEP/NCAR Reanalysis, (b) the control AGCM run (precipitation time-scale  $\tau=9600$  seconds in all latitudes), (c) the run with the Tokioka modification and reduction of precipitation timescale in tropics ( $\tau=900\text{-}9600$  seconds between  $20^{\circ}\text{S}$ - $20^{\circ}\text{N}$ ), (d) same as (c) but coupled with ocean mixed layer, and (e) same as (c) but  $\tau=1800$  seconds in all latitudes. The velocity potential is bandpassed with a 15-70 day filter to eliminate high frequencies and the seasonal cycle. The contour intervals are  $3 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ , and negative values are shaded and contoured with dashed lines.

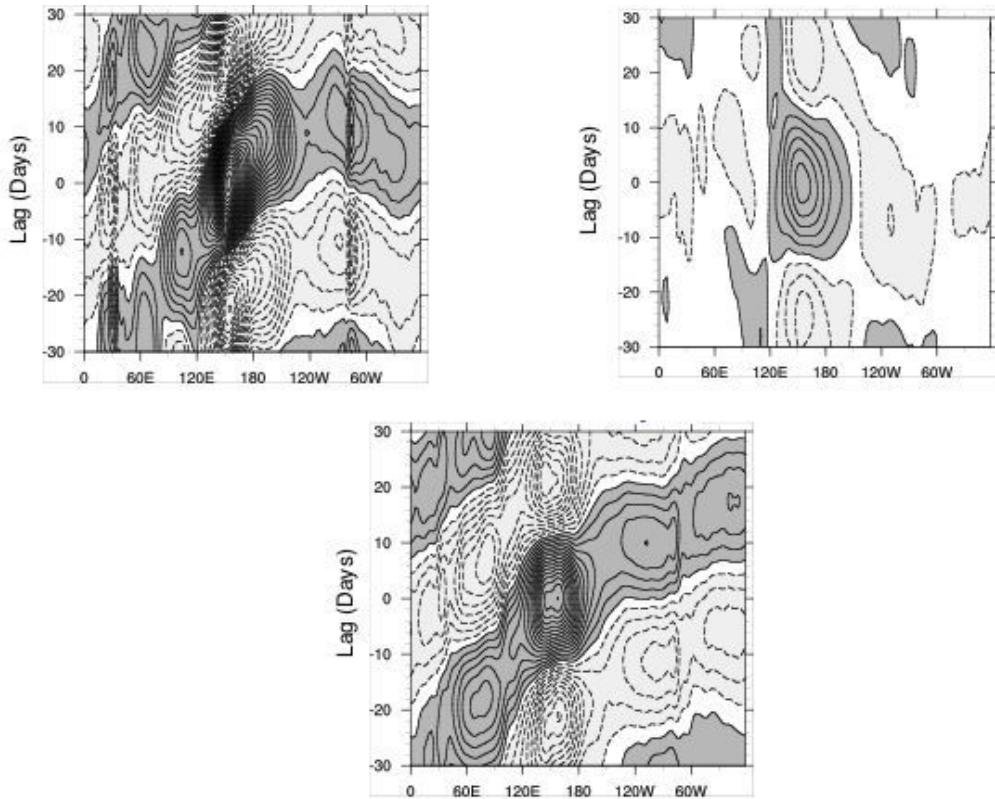
**Bill Stern** reported on the representation of the MJO in the present versions of the GFDL AGCM and CGCM as well as the impact of a number of parameterization changes. Motivating metrics for their model development mainly derived from the desire to improve AGCM climate means and reduce CGCM biases. In terms of the tropical circulation in particular, their efforts included trying to improve the “double ITCZ” problem and other tropical circulation biases, improve ENSO-related variability, and improve the simulation of the MJO and tropical storms. Overall the present version [a.k.a. Flexible Modeling System, Atmospheric Model Major Version 2/Land Model major Version 2 (AM2/LM2)] exhibits a fairly good representation of the mean precipitation pattern over most of the globe. Some of the model-data discrepancies noted include weaker ITCZs in the eastern Pacific and Atlantic Oceans, very little or no South American Convergence Zone, and weaker precipitation over the storm track region east of Asia. In terms of the tropical eastern hemisphere, possibly the most problematic feature for the MJO is the considerably weaker precipitation in the Indian Ocean, a characteristic not uncommon amongst GCMs (e.g., HadAM3, CAM2). Based on a number of sensitivity experiments, that included for example, a simple cumulus momentum transport, the above mentioned Tokioka modification (see Bacmeister and Lee presentations above), a new PBL parameterization, the addition of convective gustiness, a new convective scheme (Donner et al. 2001) and some combinations of the these modifications as well as an examination of the coupled version of the model, the following results were found. The AM2/LM2

AGCM produces a fair representation of the MJO, although the dominant power of the upper level zonal wind along the equator at wavenumber one is around 60-70 days and there is too little intraseasonal variability at higher frequencies. In addition, there is too much intraseasonal activity north of the equator during N.H. winter, an effect of the “double ITCZ” problem. In terms of these features, the new model probably has a slightly poorer/weaker representation of the MJO than the previous GFDL model (see Waliser presentation above). In addition, consistent with the earlier model version, as well many other AGCMs, the new model has very little Indian Ocean activity and little (if any) northeast propagation during summer. The sensitivity studies showed that: 1) the new PBL has somewhat of a detrimental impact on the MJO annual cycle structure (i.e. more double ITCZ emphasis) and shows less coherent propagation, 2) the Tokioka modification enhances the MJO amplitude, with more power at ~30-40 days in U200, but erroneously enhances intraseasonal precipitation in Pacific, 3) the convective gustiness enhances the MJO, including in the Indian Ocean, but it also lacked evidence of propagation and gave an erroneous enhancement of intraseasonal precipitation in Pacific, 4) the Donner convection enhanced the power at ~30-40 days in U200, improved the double ITCZ structure and propagation but gave too strong an annual cycle of precipitation and far too much intraseasonal rainfall variability in the western Pacific. Finally, the coupled model appeared to provide an improved representation of the intraseasonal activity in the Indian Ocean. However, it is not clear if this is a result or a cause of the improved means state in that region (**Figure 6**).



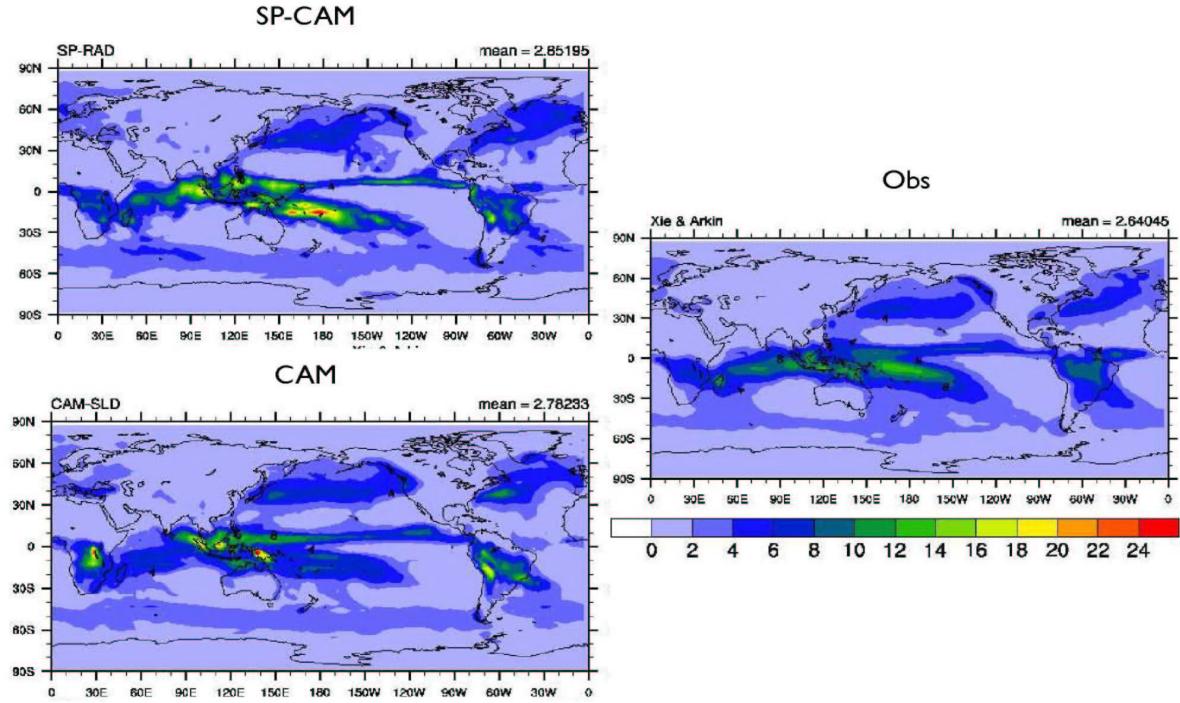
**Figure 6.** (Left) Annual mean and (Right) standard deviation of 30-90 day bandpassed precipitation (mm/day) for the GFDL AGCM (top), CGCM (middle), CMAP observations (bottom).

**Eric Maloney** presented results from a variety of sensitivity experiments using several versions of the NCAR Community Atmosphere Model (CAM) to examine tropical intraseasonal variability (Maloney and Hartmann, 2001; Maloney 2002). Two different forms of the relaxed Arakawa-Schubert (RAS) convection scheme were used: 1) standard RAS (Moorthi and Suarez, 1992), and 2) McRAS (Sud and Walker, 1999). Both schemes produce greatly improved intraseasonal variability in the NCAR CAM as compared to the standard version that uses the Zhang and McFarlane convection scheme. **Figure 7** shows the improvement produced by implementing RAS in the NCAR CAM2.0.1. Intraseasonal zonal wind variability is much stronger and characterized by realistic eastward propagation speeds as compared to the standard configuration of CAM2.0.1. The simulation of intraseasonal precipitation variability is still somewhat degraded from observations, however. This is particularly true of the NCAR CCM3.6 with McRAS convection, where positive convection anomalies tend to occur off the equator and in association with low-level easterly wind anomalies. These biases are reduced in the CAM2.0.1 with RAS convection. Several other types of model sensitivity experiments were conducted using the CAM with RAS convection. Intraseasonal variability was found to be relatively insensitive to imposition of a relative humidity threshold at the parcel launching level (cf. Wang and Schlesinger, 1999), although sensitivity was not examined for a relative humidity threshold aloft. Intraseasonal variability seems to be very sensitive to including a parameterization of convective downdrafts. Much of this sensitivity may be due to the influence of convective downdrafts on the mean humidity distribution. Inclusion of a slab ocean model generally produces more realistic intraseasonal variability. This includes much improved intraseasonal convection and wind variability over the eastern north Pacific during Northern Hemisphere summer. The sensitivity to an interactive ocean is likely a function of how well the observed phase relationship between equatorial convection and winds is simulated (Maloney and Kiehl, 2002; cf. Hendon 2000).

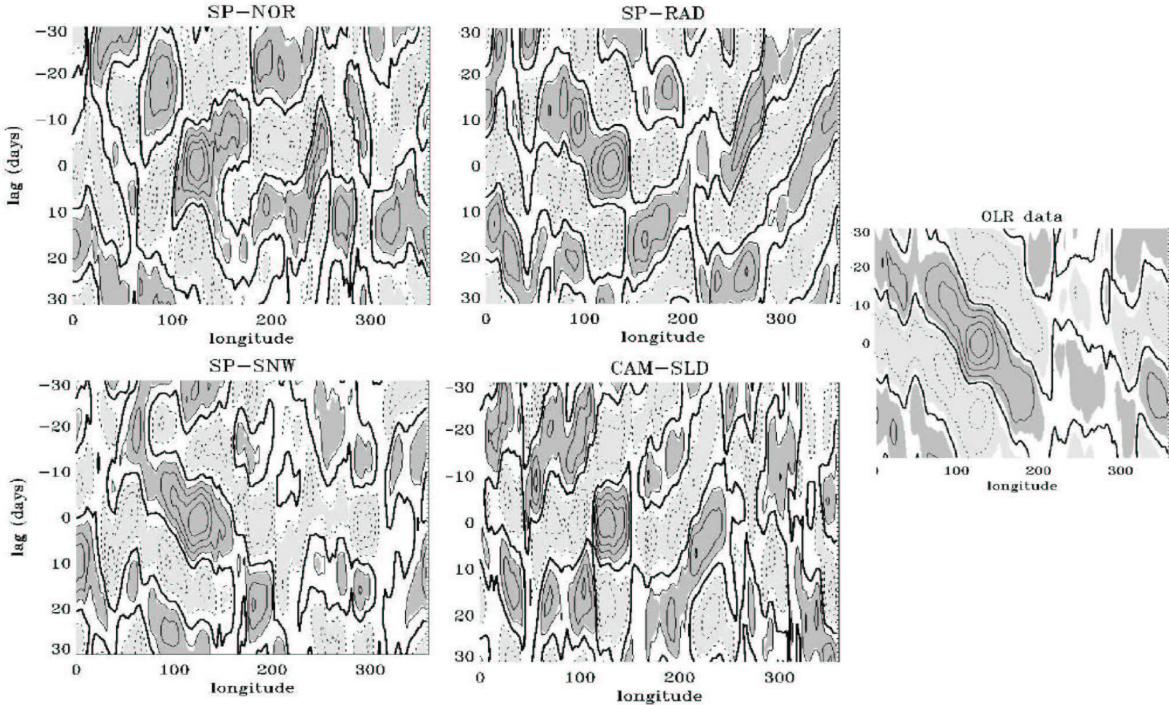


**Figure 7.** Equatorial 850 hPa 30-90 day zonal wind regressed onto itself at 150°E for (top left) CAM2.0.1 with RAS convection, (top right) standard CAM2.0.1, and (bottom) NCEP reanalysis. Fields during December-May are used in the regression. Contour interval is 0.1 m s<sup>-1</sup>, starting at 0.05 m s<sup>-1</sup>. Values greater (less) than 0.05 m s<sup>-1</sup> are dark (light) shaded.

**Marat Khairoutdinov** presented the results of using an interactive cloud-resolving model (CRM) as a parameterization scheme within a GCM, the so-called “super-parameterization” (SP) of clouds (Randall et al. 2003; Khairoutdinov and Randall, 2001; Khairoutdinov et al. 2003). In this case, a CRM is embedded into each GCM grid. Given the “large-scale” circulation tendencies from the GCM, the CRM provides the GCM with the tendencies and quantities associated with convective mixing and cloud processes. In this particular application, each NCAR Community Atmospheric Model (CAM) T42 L64 grid box has a 2-dimensional CRM embedded into it which itself has a resolution of 64 points by 24 levels. In terms of computational resources, the wall-clock time per simulated year is on the order of days using 256 processors on an IBM SP (i.e. NCAR’s “Blackforest”). Results for aspects of the general circulation were shown for several versions of the model, including the CAM with standard physics (i.e. no CRM; hereafter CAM), cases with (hereafter SP-RAD) and without (hereafter SP-NOR) interactive radiation coupling, and a case with ice-to-snow aggregation rate increased 10-fold (hereafter SP-SNW). Comparisons were shown of mean DJF precipitation rate, precipitable water, high cloud cover, and local time of non-drizzle precipitation frequency maxima for the CAM and SP-RAD cases. In regards to precipitation, the CAM considerably underestimates the precipitation associated with the SPCZ and the Indian ocean and overestimates the precipitation over the rain belt of Africa. In regards to each of these features, the SP-RAD shows considerable improvement (**Figure 8**). Commensurate with the improvement in precipitation structure is an improvement in the water vapor structure. In addition, the CAM considerably overestimates high cloud cover over most of the globe while the SP-RAD simulations shows good agreement with observations. A common problem in GCMs is a poor representation of the diurnal cycle of precipitation (i.e. normally peaks around 4 pm local time over land). A comparison to observations shows a marked improvement in this feature in all the SP runs over that by CAM, which often has the maximum frequency at around 8-11 am local time over most land regions. The results also showed a slightly better distribution of the frequency of precipitation events binned by size of precipitation event. Finally, in regards to the simulation of the MJO, the SP simulation shows (**Figure 9**) considerable improvement over the CAM, whose canonical tropical intraseasonal variability is dominated by westward propagation that is concentrated in zonal wavenumber ~5. The SP-NOR exhibits a tendency for eastward propagating activity, although such propagation appears to be accomplished through a zonally aligned series of standing waves rather than by continuous propagation. The addition of interactive radiation (SLD-RAD) appears to mitigate this problem, but the phase speed is too slow and the zonal wavenumber too high. SP-SNW appears to capture the essential elements of the propagating convective behavior of the MJO. The latter result suggests that the cloud microphysics-radiation interactions may play an important role in the organization of the MJO.



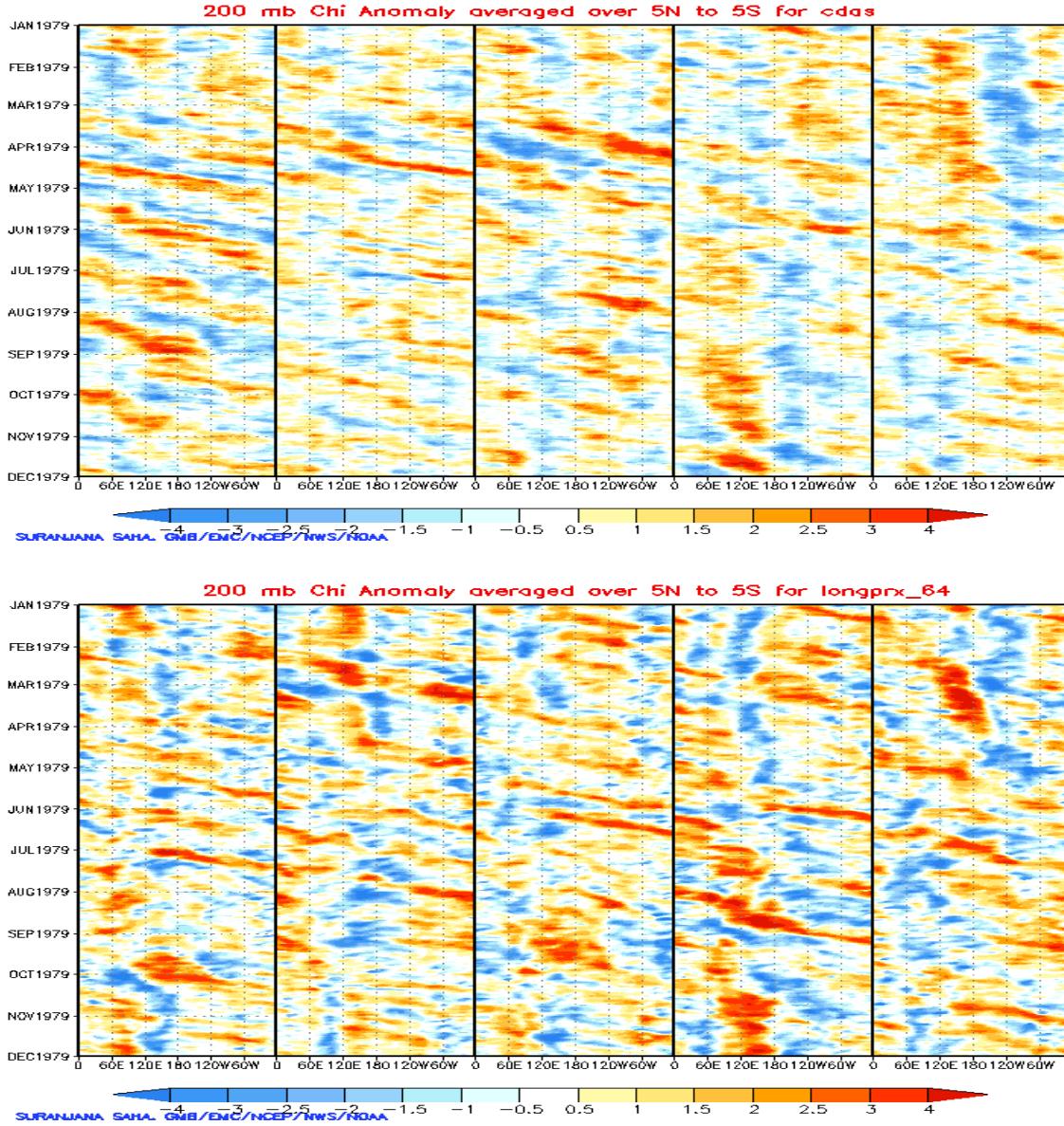
**Figure 8.** Mean DJF total precipitation as simulated with the super-parameterization CAM (SP-RAD case), standard CAM, and as observed.



**Figure 9.** Lag-correlation contours of average 10N-10S 20-100 day filtered OLR anomalies. Correlations are computed based on anomaly time series at 100E. Contour interval is 0.2. Statistically significant positive (negative) anomalies are dark (light) shaded. Significance was tested with a Student's t-test at the 95% confidence interval.

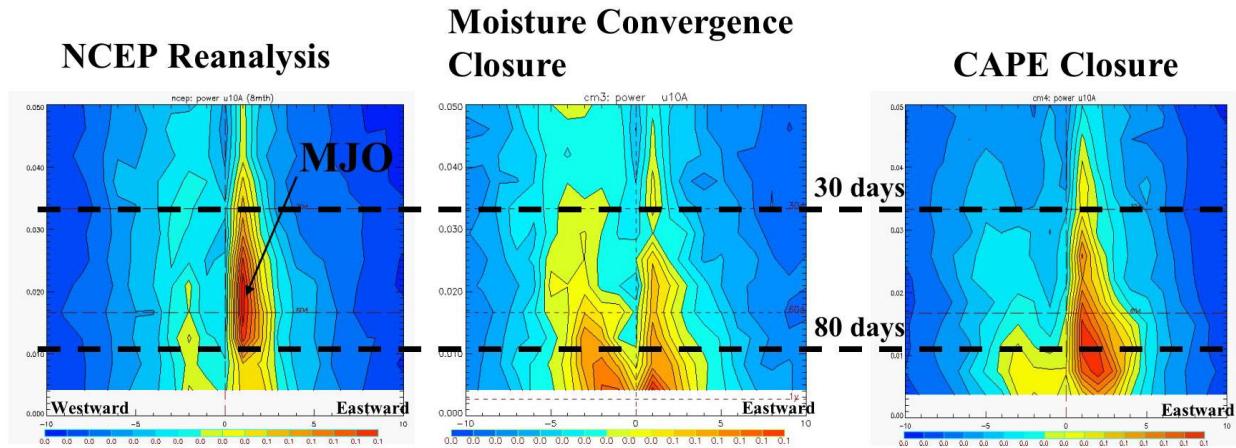
**Hua-Lu Pan** presented recent progress in the NCEP global modeling efforts to improve the week-2 to inter-annual forecasts (**Figure 10**). The present NCEP Global Forecast System (GFS) atmospheric model

was shown to display fairly realistic variability in the synoptic time scale (tropical easterly waves) and in the 40-50 day time scale (e.g. MJO) over the tropical oceans. In addition, the direct coupling of the GFS model to the Modular Ocean Model V. 3 (MOM3) was shown to generate realistic MJO signals as well as inter-annual signals in the tropics. The MJO signal in the GFS model climate simulation is very strong when forced with observed sea-surface temperature (SST) and when run with climatological SST. However, when the GFS model was run with the operational SST configuration (i.e. the observed SST anomaly is damped to zero on a 90-day time scale) for a two-year period, the composite MJO events in the forecasts yield realistic amplitude prediction but no eastward propagation. For the forecasts forced with observed SST, the composite MJO propagation improved but was still slow compared with observations. Future plans include examining MJO predictions with the coupled model.



**Figure 10.** Equatorial time-longitude diagrams of unfiltered 200 hPa velocity potential anomalies for the years 1979-83 from CDAS (top) and from simulations using specified, observed SSTs using a 64-level version of the NCEP GFS (bottom). Units are  $1 \times 10^7 \text{ m}^2/\text{s}$ .

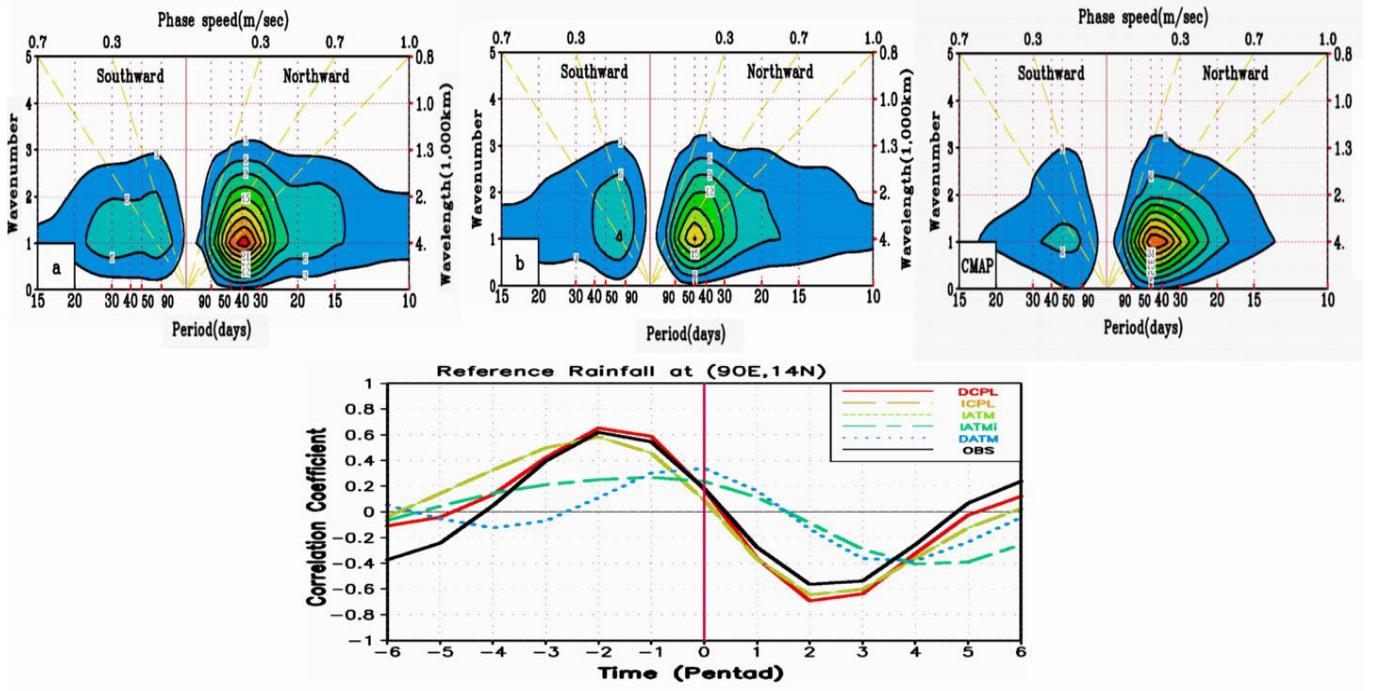
**Matt Wheeler** reported on recent experiences in simulating MJO-like variability in the global numerical models at BMRC. For climate work and dynamical seasonal prediction, the BMRC AGCM (BAM3) has T47L17 resolution with the Tiedtke (1989) mass flux cumulus parameterization scheme closed in one of two ways: moisture convergence closure or CAPE relaxation closure. The moisture convergence closure version has no MJO, as evidenced by the lack of any enhanced eastward propagating tropical variability (**Figure 11**). The CAPE closure version, however, shows a clear preference for eastward propagating variability in the intraseasonal band, albeit with a slightly lower frequency (~1/80 cpd) than observed. Along with the improved variability, the spatial distribution of the mean precipitation in the CAPE closure version is also improved; it exhibits less of a double-ITCZ problem, and is more closely tied to the distribution of warmest SSTs. The reason for the improved MJO simulation in the CAPE-closure version is hypothesized to be the result of the increased difficulty with which it takes for convection to occur in that version, through the mechanism as proposed by Wang and Schlesinger (1999). Consistent with this is that the CAPE closure version produces less convective rainfall, and instead has more large-scale condensation occurring. It is this version of the AGCM that is used in BMRC's dynamical seasonal forecast model, POAMA, which is a fully coupled model running operationally every day from the latest oceanic and atmospheric initial conditions, and shows good promise for prediction of the MJO. Analysis of the subseasonal forecasts made with POAMA since October 2002 show that it has most skill (at predicting regions of enhanced tropical convection) when the enhanced convection of the MJO is initially located over the Indian Ocean. The model readily shifts such enhanced convection eastward in a fashion that highly resembles the propagation of the MJO. More forecasts will need to be made to make a more comprehensive assessment of the model's skill. Other MJO-related simulation results, at the time of the workshop, are that coupling to an ocean appears to have little influence on the atmospheric intraseasonal variability. However, analysis since the workshop indicates that coupling increases the period of the oscillation, making it more line with observations (personal communication: Oscar Alves).



**Figure 11.** Wavenumber-frequency power spectrum of surface zonal wind ( $10^{\circ}\text{S}$  to  $10^{\circ}\text{N}$ ) for NCEP/NCAR reanalysis (left), the POAMA coupled model with the convective parameterization closed on moisture convergence (middle) and CAPE relaxation (right).

**Bin Wang** presented a comparison of AGCM and CGCM representations of the MJO and discussed their implications for prediction (Fu and Wang, 2003; Fu et al. 2003). The AGCM is an ECHAM 4 T30. The CGCM is composed of the same AGCM and a regional (i.e. tropical Indian and western Pacific Oceans) 2.5-layer intermediate model and contains no flux correction. The CGCM mean state for JJA exhibits fairly realistic patterns. The SSTs are slightly too cold ( $< \sim 1^{\circ}\text{C}$ ), namely in the western Pacific and the southern-equatorial region of the Indian Ocean. Correspondingly, the CGCM rainfall is biased slightly low in these regions but otherwise it shows good agreement compared to observations (Fu et al. 2002). In contrast to the AGCM which exhibits weak and incoherent intraseasonal variability in the Indian

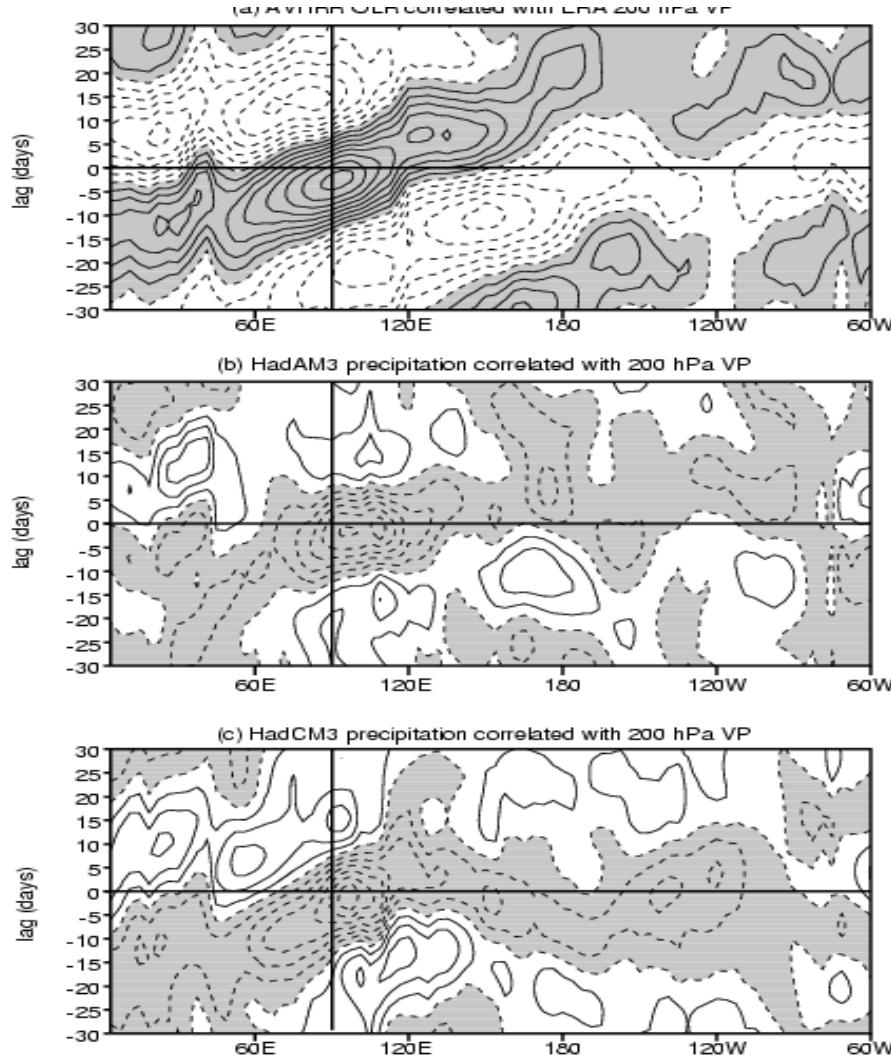
monsoon sector, the CGCM simulation shows robust northward propagating intraseasonal variability that is very reminiscent of the observed variability. In order to highlight the fundamental differences between the MJO under coupled versus specified SST conditions, results of a boreal summer MJO analysis was presented from the CGCM and a simulation done in which the SSTs from the CGCM were used as specified SSTs to the AGCM (**Figure 12**). The results demonstrate a much more realistic form and amount of northward propagating variability in the CGCM than the AGCM. In addition, the results showed that the lead-lag relation between SST and rainfall anomalies in the Indian Ocean sector is much more realistic in the CGCM than the AGCM, namely that in the observations and the CGCM the SST and rainfall anomalies are in quadrature, while in the AGCM they are nearly in phase. Such results highlight the critical importance of air-sea coupling in the simulation and prediction of the MJO (see also presentation by Waliser above).



**Figure 12.** (top) Wavenumber-frequency power spectra of north-south propagation characteristics of rainfall from longitude range 65E-95E from the U. Hawaii CGCM (left), AGCM using SSTs specified from the CGCM simulation (middle), and CMAP observations (right). (bottom) Lagged-correlation values between SST and rainfall anomalies at 90°E, 14°N for the CGCM (red-solid), AGCM using SSTs specified from the CGCM simulation (blue-dotted), and CMAP observations (black).

Peter Inness presented results concerning the propagation of the MJO in uncoupled and coupled versions of the Hadley Centre GCM in order to assess the importance of coupling in regards to simulating the essential features of the MJO. The results show that there is very little eastward propagation in the AGCM while the CGCM shows fairly realistic propagation, but only in the Indian Ocean (**Figure 13**). Examination of these results in conjunction with the means state of the low-level zonal wind show that eastward propagation tends to only occur in regions of mean westerlies. The observations exhibit mean westerlies in both the Indian Ocean and western Pacific, while the coupled model exhibits them primarily only in the Indian Ocean. Additional results suggested that the importance of the mean wind state is to produce the correct interaction between low-level wind and latent heat flux anomalies, namely that eastward propagation tends to occur where westerly (easterly) zonal wind anomalies, which are generally to the west (east) of the convection, produce positive (negative) latent heat flux anomalies. Support of this relationship comes from analysis of a flux-adjusted coupled model (i.e. one that exhibits an improved mean state in regards to the extension of the mean westerlies into the western Pacific). In this case, the

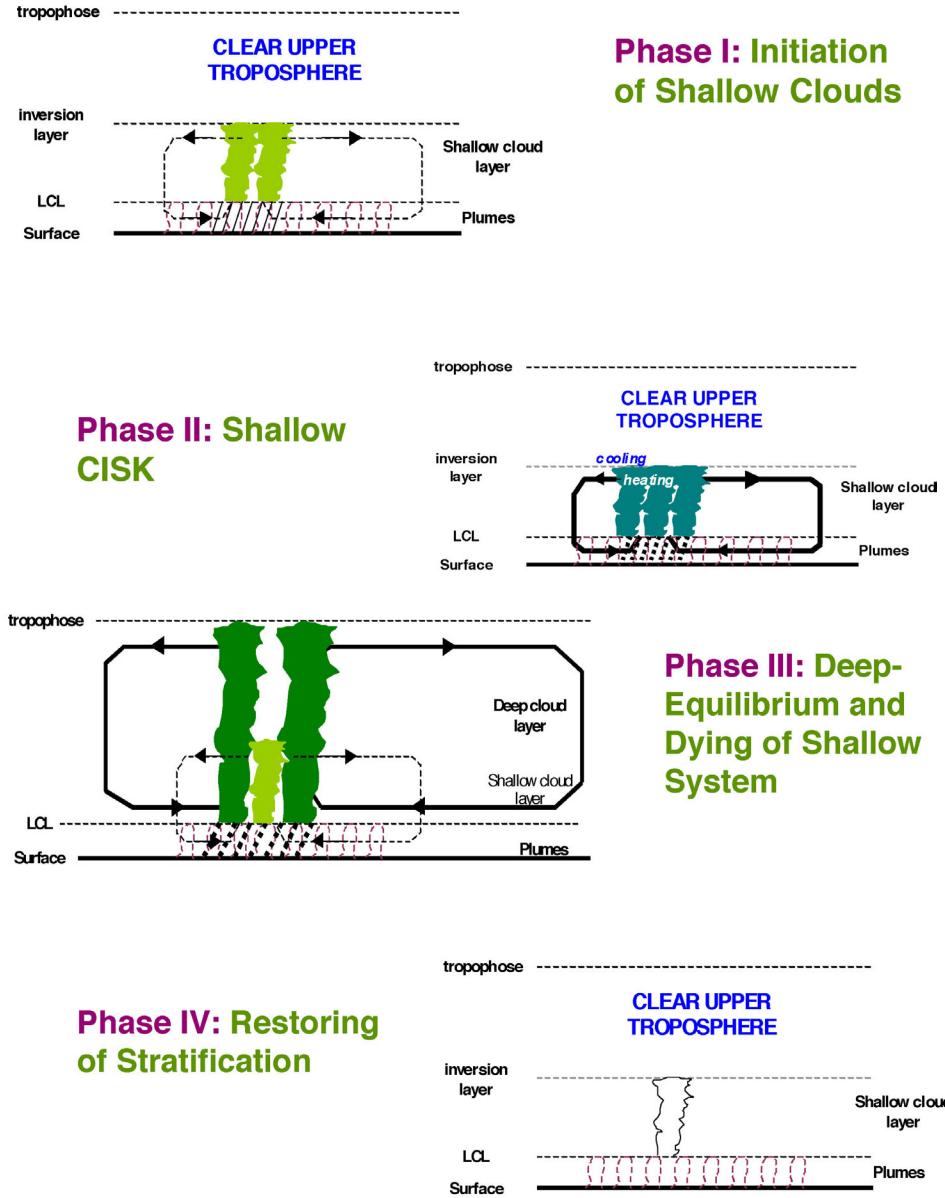
propagation of the convection does proceed well into the western Pacific Ocean, although the MJO signal in the Indian Ocean does weaken slightly. These results, along with the analogous results regarding coupled and uncoupled versions of the ECHAM GCM presented by Sperber, strongly suggests that simulating a correct tropical basic state is crucial to achieving a realistic simulation of the MJO. In addition, evidence was also presented to suggest that realistic SST variability on an intraseasonal time scale might only be achieved with high vertical resolution ( $\sim$  1-2 meters) due to the non-linear mixed-layer interactions between diurnal and longer time scales.



**Figure 13.** Lag correlation plots of OLR or convective precipitation averaged between 10N and 10S, with 200 hPa velocity potential at 90E, also averaged between 10N and 10S. (a) NOAA AVHRR OLR correlated with ECMWF re-analysis velocity potential (b) HadAM3 atmosphere-only GCM precipitation and velocity potential (c) HadCM3 coupled GCM precipitation and velocity potential. Contour interval is 0.1. All data are 20-100 day band-pass filtered.

**Zhaohua Wu** presented a theoretical examination of the role of shallow convection in producing a CISK like mechanism which in turn can lead to intraseasonal, namely MJO, variability. In this perspective, the role of shallow and cumulus congestus clouds are suggested to play an important role since, as his idealized modeling study (Wu 2003) indicates, their latent heating profile can lead to CISK, while that associated with deep convective clouds does not. Schematically, this process is represented in **Figure 14**. In the first phase, shallow cumulus develops in the face of an inversion layer and underlying instability

derived from the surface. In the second phase, the heating associated with these shallow clouds induces a CISK response, with heating (cooling) below (above) the inversion layer. The CISK response from phase II enhances the circulation/instability to the point that deep convection ensues as part of Phase III, which weakens/removes the inversion and in turn diminishes the amount and role of shallow convection. Once the deep convection, which under this mechanism cannot develop CISK, runs its course, stratification and the associated inversion layer is slowly restored in Phase IV. Overall, the adjustment times associated with each of the above Phases is on the order of 1-2 weeks, giving an overall intraseasonal time scale. Observational evidence for the operation of this scenario within the lifecycle of the MJO can be found within the COARE data record (Tung et al. 1999).



*Figure 14. Shallow-CISK-Deep-Equilibrium Mechanism (Wu 2003). Intraseasonal time scale follows from the 1-2 week time scale associated with each Phase.*

Following the modeling presentations described above, **Max Suarez** led a summary discussion meant to address the following four questions:

1. What is the status of MJO simulation in GCMs?
2. Why has this been such a persistent problem with the models?
3. What coordinated efforts are underway to diagnose and correct these problems?
4. Is it a good time for a coordinated modeling/program activity focused on MJO and if so what should be done?

### **Status of MJO simulation in GCMs**

It is well recognized that MJO simulation is a fairly generic problem in GCMs. The presentations describe above only continue to support this unfortunate state of affairs. However, the specific model shortcomings do not necessarily seem as generic as has been found in the past. For example in previous studies (e.g., Slingo et al. 1996), it was often found that the simulated MJOs were too weak and/or too fast, and often GCMs exhibited little or no MJO at all. However, as illustrated above, it is not uncommon anymore to have simulated intraseasonal variability that is stronger than observations (e.g., Fig. 2) or exhibit propagation speeds that are too slow. There seems to be a sense that more models are getting something in the way of an MJO, and no model discussed above was completely absent of an MJO-like phenomenon. Unfortunately, when a model does exhibit a relatively good MJO, we can at best only give vague or plausible explanations for its relative success. This inhibits the extension of individual model successes to other more MJO-challenged models. Moreover, it is often the case that stated successes do not stand up to a great deal of detailed scrutiny.

### **Why is this problem so persistent/pervasive?**

It has long been thought that the MJO problem likely relates to the treatment of the cumulus convection. Typically, the greatest sensitivity that the simulation of the MJO exhibits to various model “tunings” is associated with that of the convective parameterization – or closely related processes. This was fairly evident from many of the talks described above, which included a number of efforts illustrating that it was somewhat possible to “tune in” a better MJO via modifications such as the Tokioka “fix” to the Arakawa-Schubert parameterization, boundary-layer inhibition, controls on free atmospheric humidity, inclusion of gustiness, etc. While we still grapple with why certain changes lead to a better or worse MJO, it is expected or perceived that a more realistic parameterization of convection, or “no” parameterization at all (e.g., super-parameterization), should/will lead to more realistic MJO simulations.

In addition to the convection issue, it seems more of a certainty that SST coupling does play some role, though perhaps not primary, in the fidelity of a MJO simulation. All but one presentation that discussed coupling sensitivity reported improvements in the MJO simulation associated with SST coupling. These improvements appear to often affect the strength, propagation speed, relative phase between convection and SST, and spatial variability associated with the MJO. For this interaction to be properly represented, it is imperative the surface heat flux anomalies (mainly shortwave and latent) associated with the MJO be reproduced with some fidelity. This in turn involves the representation of clouds and the interactions between the heating profiles and the surface in producing a realistic boundary layer.

In regards to observations, it was noted that we clearly have enough data to determine that our GCMs have poor MJO representations but not enough information to properly tune the models or to remove ambiguities regarding parameterization choices. The most notable areas where we lack important constraining/verifying information are associated with the hydrological cycle (e.g., moisture, re-evaporation, microphysics, latent heating profiles) as well as boundary layer processes and cloud-radiative interactions. For example, how well do we represent the partition between deep and shallow

heating associated with the MJO life cycle (e.g., Fig. 14)? Within the convective phase of the MJO, how much does cloud longwave forcing influence the instability of the atmosphere?

Additional problems that appear to be important include achieving a proper representation of the basic state. Issues such as the tendency for models to produce double ITCZs, produce inadequate representations of the mean monsoon or the surface zonal wind structure in the warm pool, or exhibit biased coupled basic states can all produce limitations on the fidelity of a model's MJO representation (e.g., Figs. 1 and 13). In addition, these basic state issues are extremely important in the forecasting context since the model needs to be initialized to the observed state but then subsequently undergo an adjustment to its own basic state that can wreak havoc on the forecast.

### **Coordinated efforts**

In regards to the MJO specifically, it was perceived that beyond the AMIP and CLIVAR diagnostic studies on the MJO mentioned above, there have been no coordinated programmatic efforts focused solely on improving the MJO – apart from maybe this workshop itself. However, it was recognized that some coordinated effort by a number of modeling groups might certainly be fruitful. At a minimum this should include a set of standard diagnostics, and most notably to include diabatic and other profile information. In conjunction with the use of present and upcoming satellite missions such TRMM, AIRS and CloudSat, and possibly some simple sensitivity experiments, such a coordinated effort was recognized to be near critical for community-wide improvements to be made in regards to the MJO.

Related efforts that might indirectly contribute to improving the simulation quality of the MJO are those associated with the Atmospheric Climate Process Teams (CPTs) – a joint effort by NSF/NOAA to fund research on highly focused research areas. In addition, Tsendgar Lee noted that he anticipated that the NSIPP science team would be enhanced/enlarged via one or more funded research opportunities by NASA with the expectation that some of the effort would be directed at the cumulus and/or MJO problem(s). It is hoped that diagnostic studies through AMIP and CMIP might lead to some useful avenues of investigation as they have in the past, although the lack of vertical structure information afforded by the required high frequency output presents somewhat of a limitation to what can be expected/accomplished.

Apart from that described above, it was not apparent that there were any international efforts underway, although it was encouraging that ECMWF will be hosting a workshop focused on the MJO in November (T. Palmer – personal communication). It is hoped that with workshops such as this, and what might develop from the ECMWF workshop, that more coordinated programmatic efforts on the MJO might be initiated.

### **What should we do?**

While a number of possible avenues for making headway on the MJO modeling problem were discussed it was recognized that no single avenue alone was expected to solve the problem in the near-term. Thus, it was recommended that a number of directions be pursued which included:

- *Utilize sub-seasonal prediction*

This would involve making short-term (e.g., 30-60 days) forecasts initialized from observed initial conditions and examining the evolution of the model error (e.g., activities from Section II.A and II.C). Such an analysis could be focused on periods of strong versus weak MJO activity and sample different phases of the MJO life cycle. In contrast to emphasizing skill scores under such a scenario, the analysis would focus on how the modeled MJO deteriorates, the difference in modeled versus observed MJO strength and propagation speed, the adjustment of the model to the climatology of the

analyses used as initial conditions (if applicable), etc. The advantages of this method can be that the simulations are relatively short and ensembles (if needed) can be relatively small. This might facilitate a more complete exploration of the realizable parameterization space associated with convection, clouds, boundary layer, etc.

- *Targeted AMIP-like experimentation and analysis*

This would follow along the lines of previous AMIP-like analyses with the possibility of including some specific parameterization changes and the objective of determining what relatively poor MJO models have in common and what relative good MJO models have in common. Some effort along these lines was included in the study by Slingo et al. (1996). Additional issues/quantities that need to be addressed along the above lines involve latent and radiative heating profiles, the relative moistness of the atmosphere in general, particularly the upper troposphere, how sensitive the surface fluxes are to the diabatic heating, the size and variability of a model's tropical CAPE, etc. Yet to be performed is a simple analysis that would take one or more relatively good MJO models and examine how its vertical profiles of moisture, diabatic heating, etc. compare with 1 or more models that have a relative poor MJO. This alone, or better yet in conjunction with reanalysis data or data from satellite missions such as TRMM or AIRS, might help elucidate what are important features that must be captured to properly, or at least better, represent the MJO.

- *Idealized modeling frameworks*

While there were only one or two presentations that involved more idealized modeling frameworks (e.g., Lee and Wu), it was perceived that more could probably be learned from some simplified GCM scenarios (e.g., aqua or swamp planets) as well as more idealized simple models.

- *Focused workshop and workgroups*

As indicated above, it was generally agreed that having coordinated workshops, such as the previous subseasonal (Schubert et al. 2002) and present MJO workshop, or the upcoming MJO workshop to be held at ECMWF, are vital to sustaining an viable effort at remedying the MJO problem in GCMs. These workshops provide an ideal pathway for communication between model development teams, MJO research, and observational/satellite programs. Moreover, it was thought that through these workshops, a set of basic model output and diagnostics should be defined in order to better take advantage of simulations that will be undertaken naturally as part of model development or model involvement in activities that are not solely directed towards the MJO.

## C. MJO Experimental Prediction Program

This session was opened with remarks from **Duane Waliser** who described the history behind the development of the MJO Experimental Prediction Program. As discussed, one important component of this development was the recent activity in the area of empirical prediction of the MJO (e.g., Waliser et al. 1999; Lo and Hendon 2000; Wheeler and Weickmann 2001; Mo 2001; Jones et al. 2003). Such activity not only indicated a strong grass-roots interest in the problem but also resulted in schemes that provided useful skill with lead times of 2-3 weeks. The program arose more formerly based on two parallel streams of activity. The first was the occurrence of the first subseasonal workshop discussed in the Introduction (Schubert et al. 2002) and the recognition of the importance of the MJO in regards to the potential skill to be had from subseasonal predictions. The second stream of activity ensued from the priorities and recommendations of the US CLIVAR Asian-Australian Monsoon Working Group (AAMWG). In their 2001 research prospectus (AAMWG, 2001) as well as their Process Study Work Plan, delivered to the US CLIVAR Scientific Steering Committee (SSC) and discussed at their SSC-9 (Sep. 2002) and SSC-10 (Jan. 2003) meetings, recommendations were made to develop an experimental

prediction program due to the significant influence that the MJO has on the character and evolution of Asian-Australian monsoons.

The above streams of activity led to an E-mail discussion among a number of MJO forecast enthusiasts during the summer and fall of 2002 to develop the framework for such a program. Crucial to the implementation of the program was a sponsor that would provide technical and electronic management, one with interest and expertise in subseasonal phenomena and forecasting. Fortunately, due to their intrinsic and overlapping objectives, along with their significant and wide-ranging expertise in the areas of weather and climate diagnostics and forecasting, the Climate Diagnostics Center/NOAA (see [www.cdc.noaa.gov](http://www.cdc.noaa.gov)), via discussions with Klaus Weickmann and Randall Dole, graciously offered to be the program's sponsor. Based on the preliminary framework for the program and the realization of a sponsor, letters were sent to a number of forecast agencies, modeling centers and empirical MJO modelers inviting them to participate in the program (see Appendix IV). With an overwhelming majority of the responses to the invitations being positive, the program proceeded to the implementation phase. It was in this session that the program's formal framework and implementation details were discussed and worked out.

Following the above introductory remarks and background information, **Klaus Weickmann** proceeded with a brief description of the motivation and plans for the program. This involves exploiting the program not only for its obvious objective of forecasting MJO variability but as a basis for model intercomparison studies. This latter includes using the forecasts and biases in model error growth as a means to learn more about, and possibly rectify, model shortcomings but also includes using the empirical models to provide some measure of the expectations that should be attributed to the dynamical models in terms of subseasonal predictive skill. In the future, once it is established that some skill can be derived from the models contributing to the experimental program, whether empirical or dynamical, efforts would be made to incorporate this information into formal week 2 and monthly predictions from the forecast agencies. In addition to the above, the information provided by the experimental program would more easily provide a means to routinely start to diagnose, and provide some attribution of, subseasonal weather/climate anomalies.

Based on the above motivation, the overarching targets of the program, as they relate to the MJO, were outlined. This mainly includes skillful predictions of the tropical intraseasonal variability, namely the MJO, with lead times of 2-4 weeks (~5-30 days). In terms of skillfully predicting tropical variability at these lead times, it is recognized that the state of the MJO and its evolution is crucially important. In terms of extra-tropical forecasts, the skillful prediction of the MJO is perceived to be somewhat, or at least intermittently, important for deterministic extra-tropical weather forecasts during week 2 (e.g., Ferranti et al. 1990; Whitaker and Weickmann 2001). At lead times of 3 to 4 weeks, the prediction of the MJO may be helpful in foreshadowing regime changes in the extra-tropical flow. In both the tropical and extra-tropical cases, skillful MJO forecasts could lead to useful predictive information on the likelihood of extreme events (e.g., US west coast storms, hurricane/typhoon activity; Higgins et al. 2000; Jones 2000; Maloney and Hartmann 2000; Mo 2000). At lead times longer than 4 weeks, there is little expectation at this time for the deterministic aspect of the MJO forecasts to be of much use (e.g., Krishnamrti et al. 1990; Chen et al. 1993; Waliser et al. 1999; Lo and Hendon 2000; Wheeler and Weickmann 2001; Mo 2001; Jones et al. 2003, Waliser et al. 2003a,b). At these lead times, the problem equates to a seasonal prediction where initial condition importance gives way to boundary condition (e.g., SSTs) importance, and at the moment, for these lead times, it isn't obvious that even the statistics associated with the activity level of the MJO are overly sensitive to the SST (e.g., Slingo et al. 1999; Gualdi, et al. 1999; Hendon et al. 1999; Waliser et al. 2000; Bergman et al. 2001).

Once the motivation and objectives of the program were outlined, Klaus described proposed framework and solicited comments and suggestions for modifications. Most of the discussion revolved around what variables to include and what to recommend in terms of temporal resolution of the forecasts, the update frequency of the forecasts, and the forecast length. Given that the forecast centers play a pivotal role in this program, and that it is unlikely that, at least initially, we will be able to get all the forecast centers to accommodate a given long-range (e.g., 30-60 days) prediction format for the purposes of this

experimental program, it is recognized that the proposed framework is largely only a guideline for the participants to try to accommodate. In any case, the discussion worked to develop a framework that sought a balance between what most centers and empirical modelers could accommodate and would still be useful for the program.

Additional discussion highlighted the importance of the climatologies from which to compute anomalies. Ideally, it is understood that a re-forecast data set be constructed which is a set of hindcasts that covers a sufficiently long period (~decade(s)) from which a lead-dependent climatology can be constructed, and thus removed from the forecasts to produce true lead-dependent anomalies. At present such a resource is only available for the NCEP-derived model run at CDC (Hamill et al., 2003). Short of this being available, it is hoped and recommended that any given forecast center will at least have a climatology based on a long-term simulation of their current models. In the case that this is not available, it is left up to the forecast center to determine how to produce anomalies, with the suggestion that using one of the re-analysis data sets for climatology might be one option. In this latter case, the model bias will be embedded in the forecast at all lead times. The need for coupled forecasts and ensemble forecasts was also discussed. In line with the above discussion, it is not expected that uniformity can be imposed in these two areas. However, both coupled and ensemble forecasts are considered highly desirable and will be utilized if available. Finally, some aspects and content from the preliminary version of the Experimental Program web site (<http://www.cdc.noaa.gov/map/images/mjo/>) was presented and discussed. This led to a number of suggestions to be incorporated into future versions. The “final” version of the framework regarding participatory contributions to the Experimental Program, worked out in this session, is provided in Appendix V.

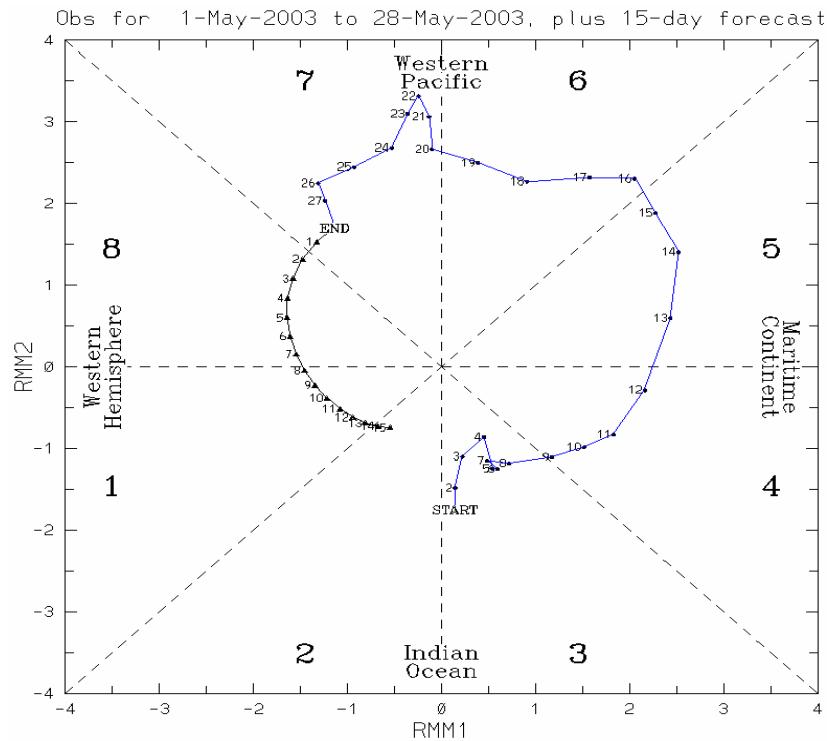
Following the discussion of the implementation framework for the MJO experimental prediction program, a number of empirical modelers discussed aspects of their schemes and forecast skill. This part of the session was motivated by the expectation that the skill from the empirical/statistical prediction strategies will be the benchmark by which the dynamical models will be assessed. Moreover, since the nature of the empirical models is more heterogeneous in their design, predictands, etc., as compared to the dynamical NWP models, it was thought that having an overview of these schemes would be especially useful. **Matt Wheeler** began this part of the session by describing MJO empirical forecasting efforts at BMRC. These efforts include two sorts of products. The first was introduced a few of years ago and involves wavenumber-frequency analysis of OLR data and its interpretation in terms of convectively-coupled equatorial modes (Wheeler and Kiladis, 1999; Wheeler and Weickman, 2001). Specifically, Fourier filtering of daily-updated global OLR is performed for specific frequencies and zonal wavenumbers associated with the MJO. The filtered fields obtained for times before the end of the dataset may be used for monitoring the MJO (as well as other equatorial modes, e.g., Kelvin or Mixed Rossby-Gravity), while the filtered fields obtained for times after the end-point may be used as an MJO forecast<sup>1</sup>. Validation analysis suggests that useful skill for these forecasts range between about 15-20 days.

The second BMRC effort, developed more recently, builds on the study by Lo and Hendon (2000) and utilizes what is referred to as an all-season Real-time Multivariate MJO (RMM) index (Wheeler and Hendon, 2003)<sup>2</sup>. The index results from projecting daily data onto the first two modes of a combined EOF of tropical (15°N-15°S) OLR, and zonal winds at 850 and 200 hPa. This projection onto the EOF pair, along with the prior removal of an estimate of the data’s very low-frequency components (e.g., ENSO) via their relationship to interannual SST variability, remove the need to perform time filtering to identify the MJO. The values of the index (actually two indices, one amplitude time series for mode 1 (RMM1) and one for mode 2 (RMM2)) at any given time can be used for monitoring (**Figure 15**). In addition, seasonally and time-lag dependent regression can be used to forecast the evolution of these indices or any associated field, using as predictors RMM1 and RMM2 at the initial day (**Figure 15**) & (**Figure 16**). Skill scores in terms of correlations of predicted versus verifying values of RMM1 and RMM2 are about 0.6 for 12-day forecasts, and 0.5 for 15-day forecasts. The advantages of the method

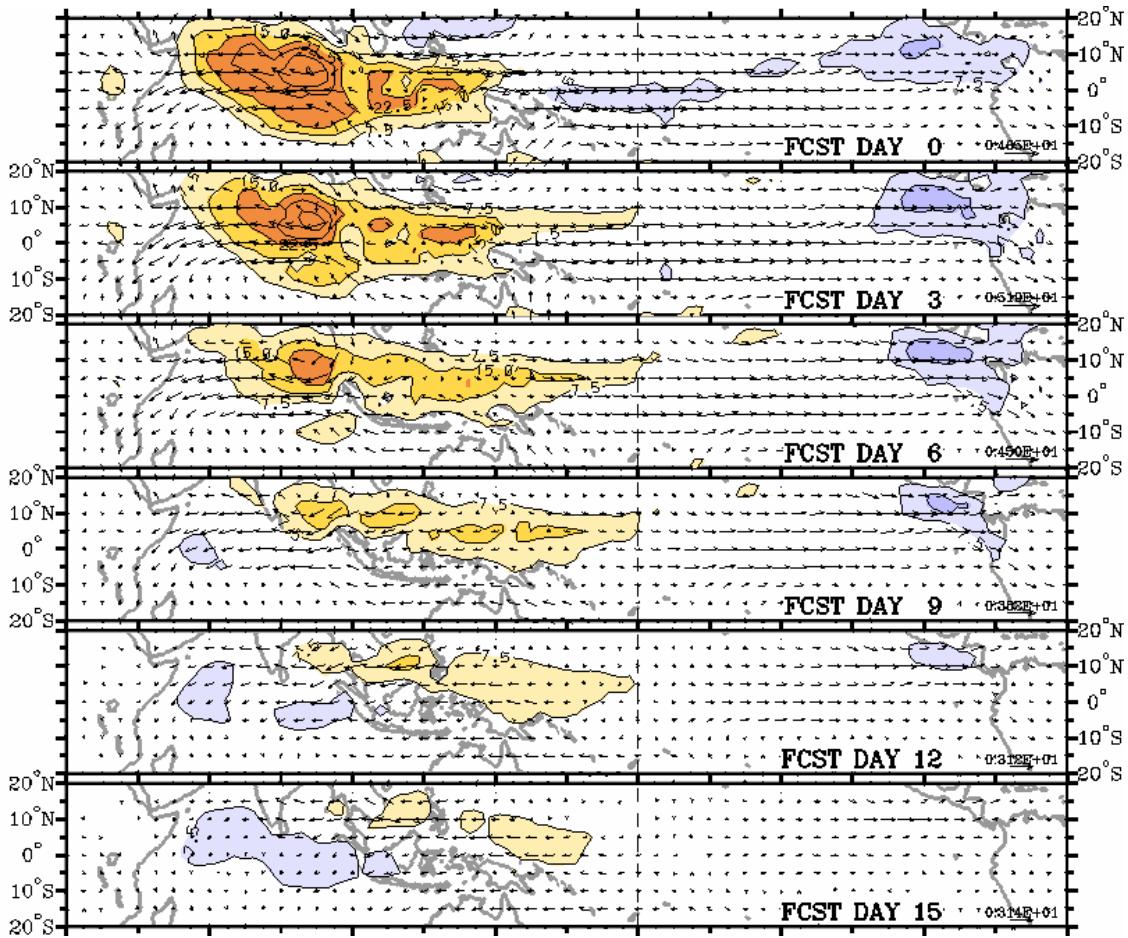
<sup>1</sup> [http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/OLR\\_modes/index.htm](http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/OLR_modes/index.htm)

<sup>2</sup> <http://www.bom.gov.au/bmrc/clfor/cfstaff/matw/maproom/RMM/index.htm>

are that it has a seasonal dependence built in and it can be easily adapted for forecasting nearly any field related to the MJO.



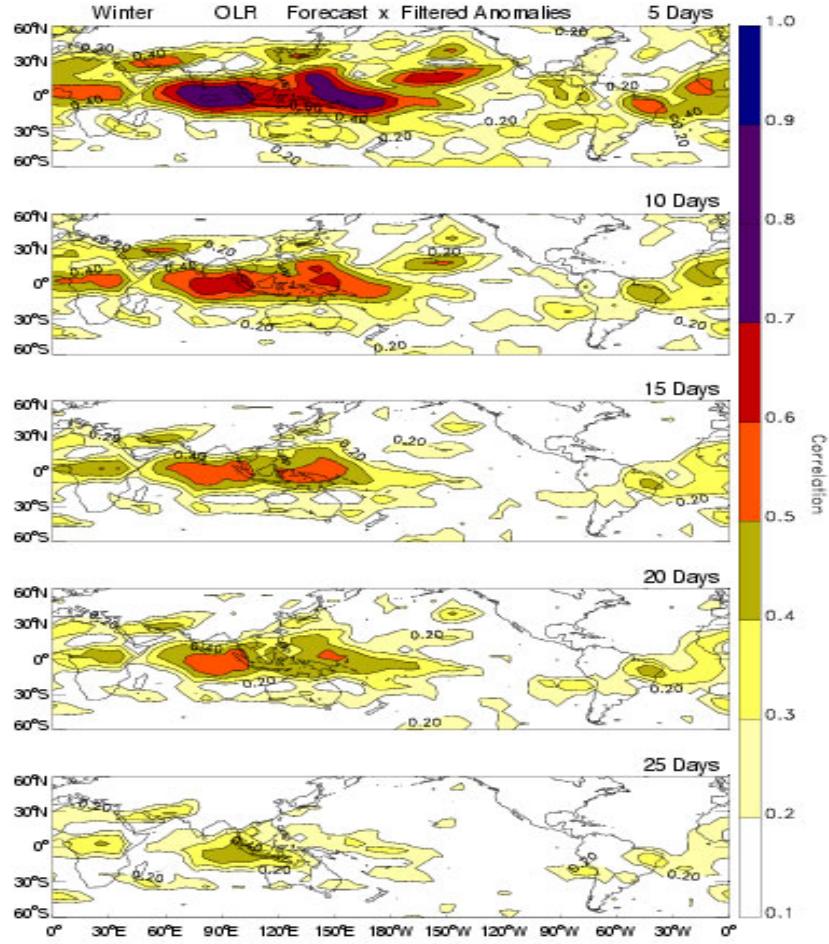
*Figure 15. MJO observations (black points connected by blue line) and 15-day forecast (triangles connected by black line) as presented in phase space defined by the normalized amplitude time series of the EOF pair that describe the MJO (RMM1 and RMM2). This was an actual forecast produced on the 29<sup>th</sup> of May using RMM1 and RMM2 observed on the 28<sup>th</sup> of May as the predictors.*



**Figure 16.** Lagged regression forecast of OLR anomalies (shading) and 850 hPa wind anomalies (vectors) of the MJO for the same 15-day forecast period as presented in Figure 15. Day 0 refers to the time of the initial condition on the 28<sup>th</sup> of May. Day 15 is the forecast for the 12<sup>th</sup> of June. Contour interval is  $7.5 \text{ W m}^{-2}$  with no zero contour shown. Orange shading for OLR  $> 7.5 \text{ W m}^{-2}$  and blue for OLR  $< 7.5 \text{ W m}^{-2}$ .

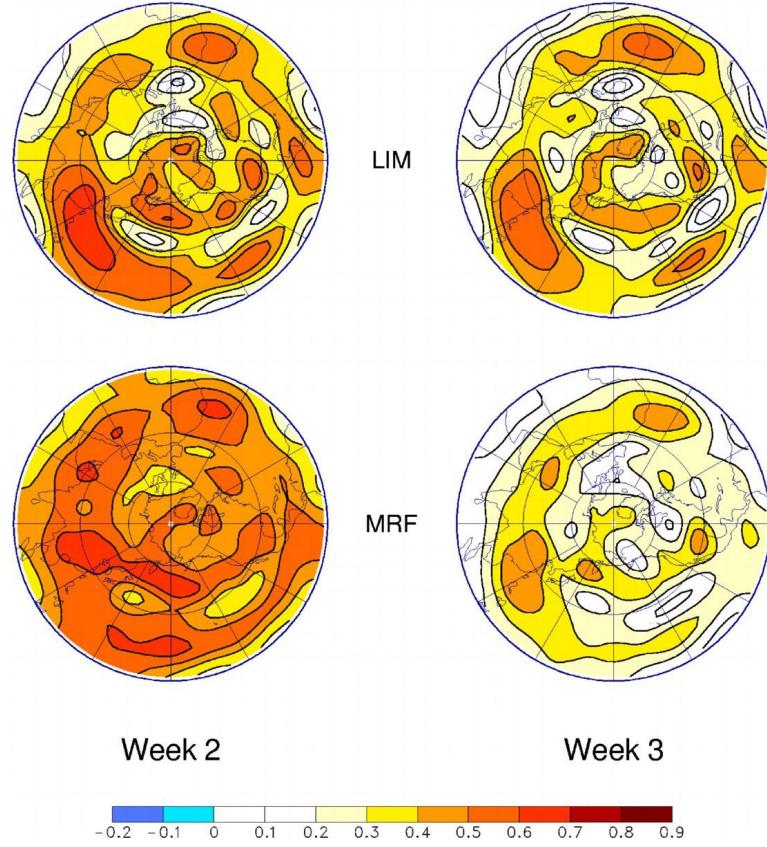
**Charles Jones** followed by presenting the most recent version of his empirical forecast scheme (Jones et al. 2003). The model is based on bandpassed (20-90 days) OLR, and zonal winds at 850 and 200 hPa. Upon filtering, a combined EOF of the three fields is computed and then the principal components (PCs) are separated into summer and winter. A seasonally dependent regression model is then formed at every given lead between 1 and 10 pentads. The model utilizes the first five principal components (PCs) from the EOF and the five most recent values of the PCs. The model is found to exhibit winter and summer skills comparable to that described above (**Figure 17**) and has been applied in real-time<sup>3</sup>.

<sup>3</sup> [http://www.icesc.ucsb.edu/asr/mjo\\_forecasts.htm](http://www.icesc.ucsb.edu/asr/mjo_forecasts.htm)



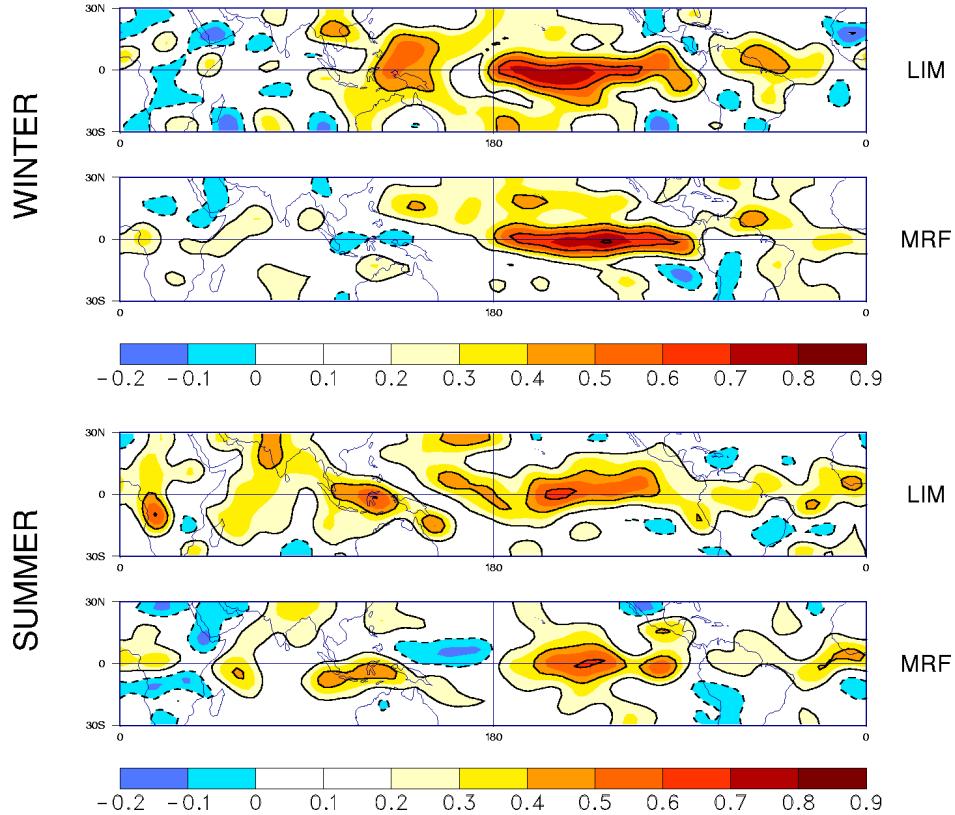
**Figure 17.** Correlation between forecasts and validation values of 20–90 days anomalies of OLR. First contour is 0.2 and interval is 0.1. Lead times are indicated in each panel. Validation is performed on 11 winter seasons of independent data.

**Matt Newman** provided an overview of the methods, skill and plans associated with the Linear Inverse Model (LIM; Winkler et al. 2001; Newman et al. 2003). The LIM is based on NCEP/NCAR reanalysis data that has had the annual cycle removed, been smoothed with a 7-day filter, and been reduced by EOF decomposition. The specific fields used include global 250 and 750 hPa streamfunction and tropical column-integrated diabatic heating. For the northern hemisphere winter (summer) model, the first 30 (30) streamfunction and 7 (20) diabatic heating EOFs are used. The advantage of the model is that it includes both tropical (in terms of diabatic heating) and extratropical (in terms of streamfunction) forecasts. Thus the interaction between the fields can be more readily examined and diagnosed. For northern hemisphere forecasts of 250 hPa streamfunction, the MRF slightly outperforms the LIM at lead times of 2 weeks. On the other hand, the LIM outperforms the MRF at lead times of 3 weeks (**Figure 18**). For tropical forecasts of diabatic heating, the LIM slightly outperforms the MRF at lead times of 2 weeks, for both northern hemisphere summer and winter, particularly in regions where the MJO is most strongly affecting the diabatic heating field (**Figure 19**).



*Figure 18. Comparison of local anomaly correlation of 250-hPa streamfunction Northern Hemisphere wintertime forecasts based on week 2 (left) and week 3 (right) forecasts made during DJF 1978/79-1999/2000 for the LIM (top) and MRF98 (bottom). Contour interval is 0.1 with negative and zero contours indicated by blue shading and dashed lines. Shading of positive values starts at 0.2; redder shading denotes larger values of correlation, with the reddest shading indicating values above 0.6.*

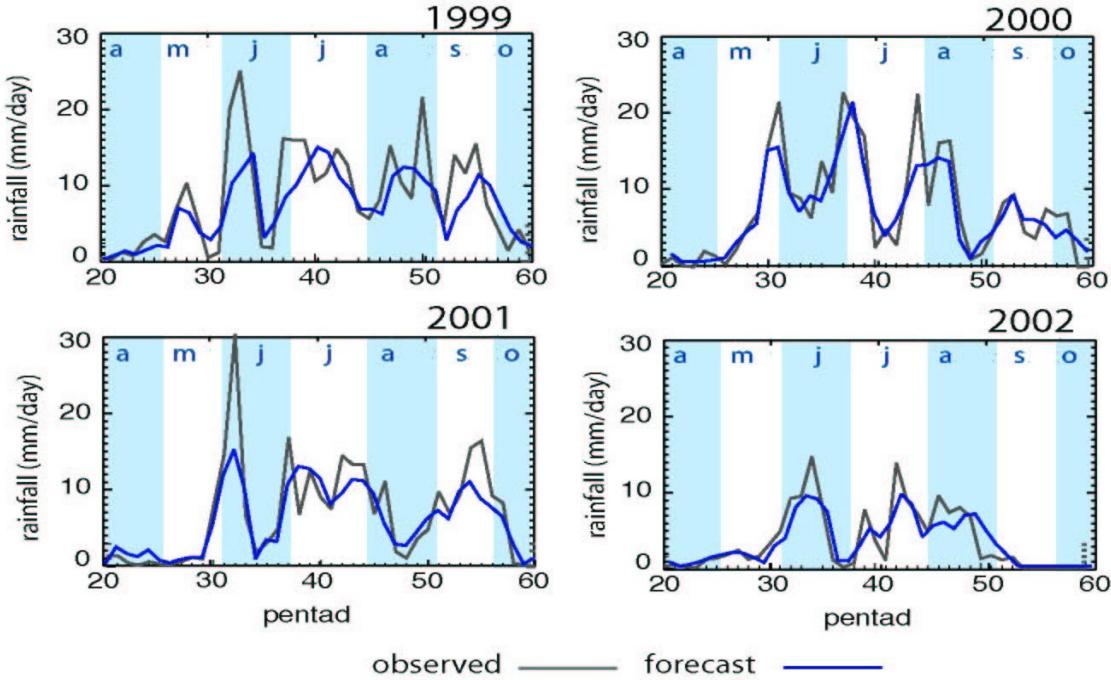
### Anomaly correlation of Week 2 Diabatic Heating forecasts



**Figure 19.** Comparison of local anomaly correlation of column integrated diabatic heating for Northern Hemisphere winterime forecasts made during DJF 1978/79-1999/2000 (upper panels) and summertime forecasts made during JJA 1979-2000 (lower panels) based on week 2 forecasts from the LIM and MRF98. Contour interval is 0.1 with negative and zero contours indicated by blue shading and dashed lines.

**Carlos Hoyos** and **Dan Collins** described a new effort at predicting empirically Indian district rainfall and the Brahmaputra and Ganges river discharge into Bangladesh on 20-25 day time scales. The empirical model is physically based with predictors drawn from the composite structure of the monsoon intraseasonal variability. In essence the model is Bayesian and uses a wavelet technique to separate significant spectral bands. The system is described in detail in Webster and Hoyos (2003). The model has been used successfully to predict rainfall in hindcast mode (**Figure 20**). It has also been used in a real time operational mode this summer in the Climate Forecast Application in Bangladesh (CFAB) project as part of a three-tier forecasting system wherein seasonal outlooks are given every month for the ensuing 6 months, a 20-25 day forecast is prepared every 5 days and a 1-5 day forecast is prepared daily. These forecasts of precipitation and river discharge have been integrated into the Bangladesh system on an experimental basis.

## 20-day precipitation forecasts Ganges Valley

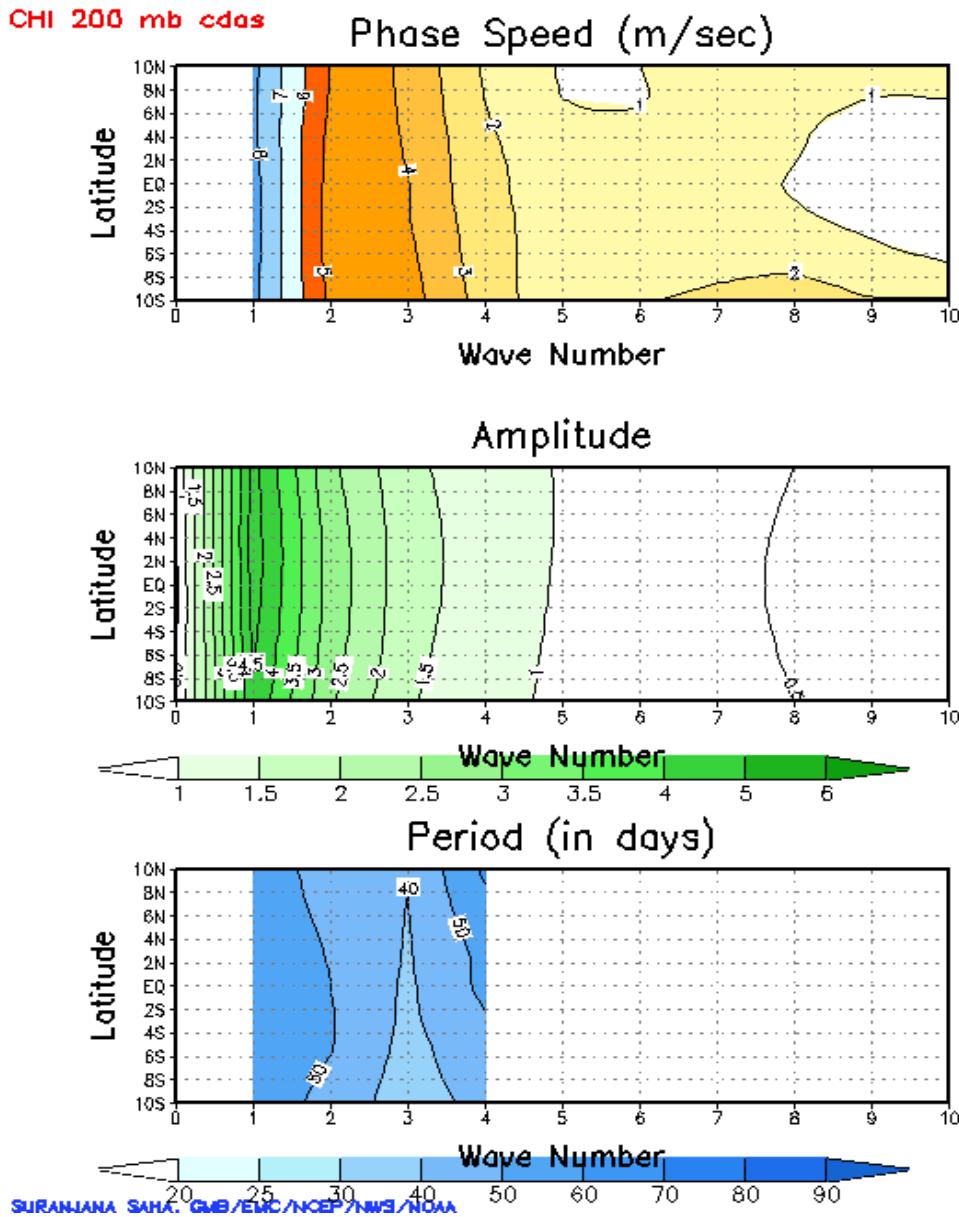


**Figure 20.** 20-day forecasts of precipitation averaged over the Ganges Valley for the summers of 1999-2002. Blue lines indicate 20 day (4 pentads) forecasts. Dark gray lines indicate observations of the area-averaged GPI precipitation product. The forecast scheme manages to forecast the phase of the rainfall variability with significant skill. Occasionally, the amplitude is underestimated by the scheme. Blue and white background denotes months.

**Suranjana Saha** closed this session with a presentation that included two parts. One involved the empirical forecasting scheme developed by Huug van den Dool<sup>4</sup> and the other described a number of modeling and monitoring efforts related to subseasonal variability that are underway by personnel at Global Climate and Weather Modeling Branch (GCWMB). In regards to the former, the forecasting scheme is referred to as empirical wave propagation (EWP). EWP is a 'phase-shifting' technique that allows one, in the diagnostic step, to determine the amplitude weighted average climatological phase speed of anomaly waves (e.g., equatorial propagation of the MJO), where the waves are represented as either zonal or spherical harmonics. The diagnostic step results in a table of phase speed (or one day displacement) for waves in the anomaly field as a function of zonal wavenumber, calendar month and latitude, based on a specified (model or observed) data set. **Figure 21** shows such information based on the diagnostic analysis of 5 years of CDAS 200 hPa velocity potential data for all seasons. In this case, the wavenumber 1 disturbance propagates at about 5 m/s and has an amplitude of about  $5 \times 10^6$  m<sup>2</sup>/s. In the forecast step, given an initial anomaly field, one projects the initial condition onto sines/cosines or spherical harmonics, then propagates each wave over the longitude displacement provided by the Table, and transforms the field back to physical space.

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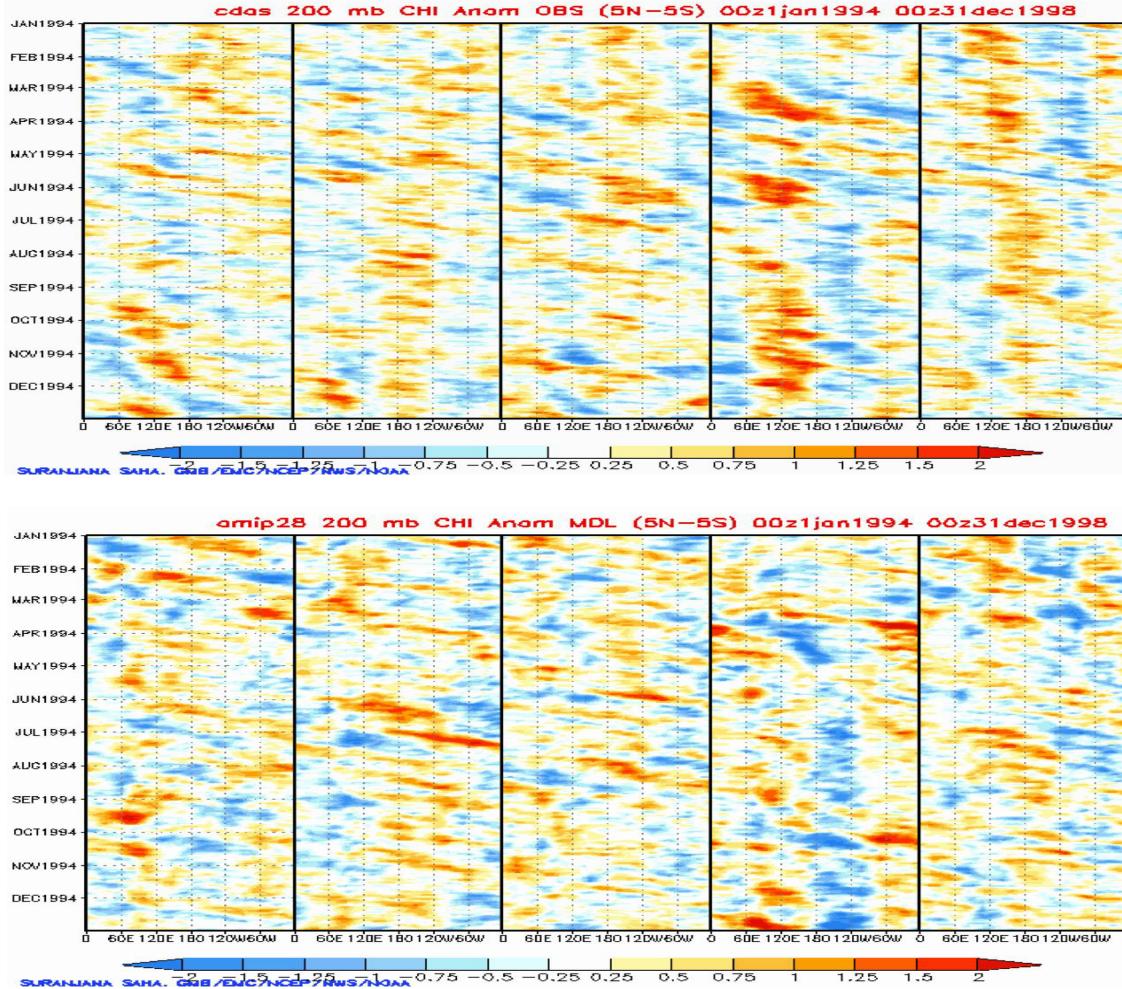
<sup>4</sup> More information on this technique as well as real-time and archived forecasts can be found at: <ftp://ftpprd.ncep.noaa.gov/pub/cpc/wd51hd/mjo.html>.

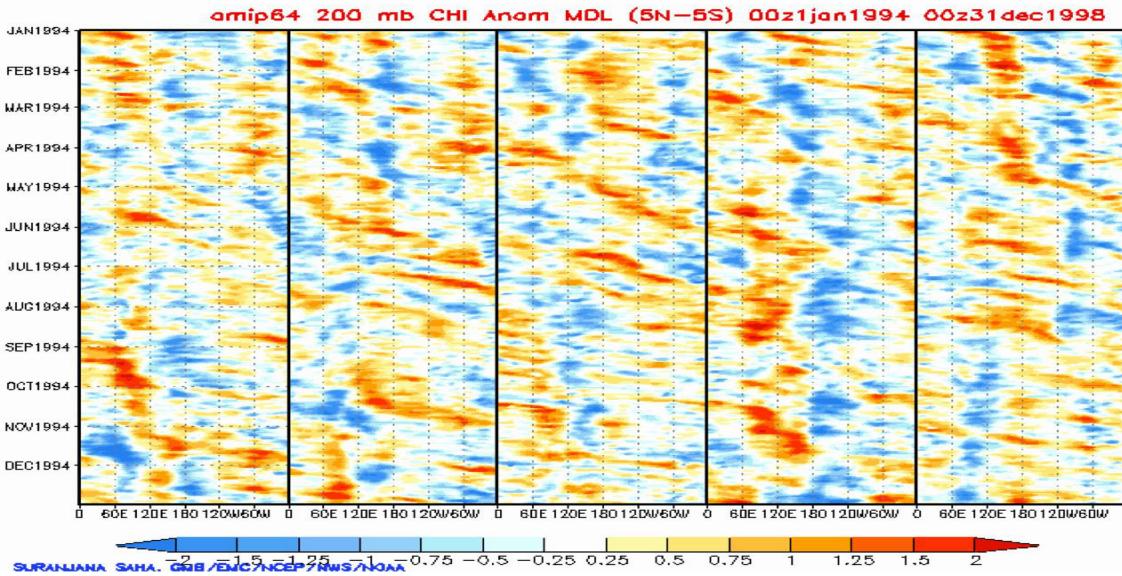


*Figure 21. Diagnostic information provided by the EWP technique for 200 hPa velocity potential anomalies from CDAS for all seasons combined for the years 1979-83.*

In regards to the modeling and monitoring efforts, a brief presentation was given describing MJO sensitivity in a number of NCEP/GFS model simulations. In all, these sensitivity studies involved about 15 1-year simulations using SSTs specified from observations with variations on horizontal and vertical resolutions as well as on a number of physical parameterizations including convection. In addition, a few simulations were extended to 5 years, and two extended to 25 years. The main results shown at the workshop included a comparison of equatorial time-longitude diagrams of 200 hPa velocity potential anomalies from a subset of the 5-year simulations to the analogous field from the climate data assimilation system (CDAS). The model subset included 28-level and 64-level versions of the NCEP/GFS, as well as 28-level and 64-level versions of the coupled NCEP/GFS. In all cases, the model variability looked to be greatly improved over past versions of the NCEP/GFS, mainly in regards to the

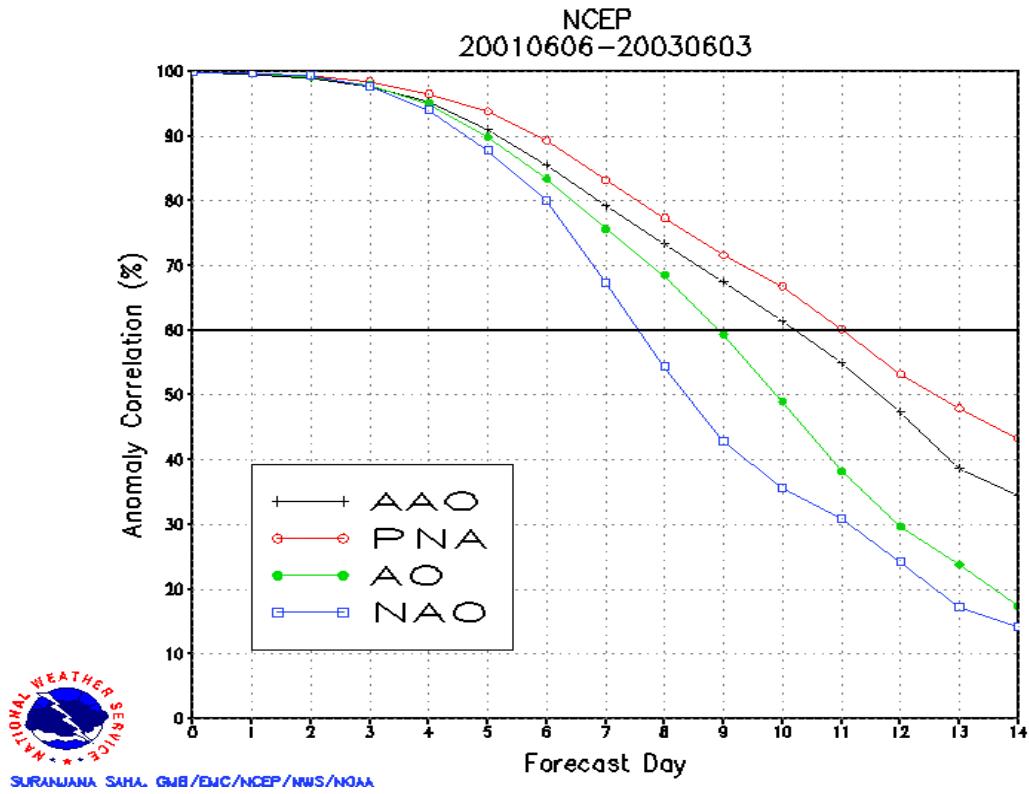
fact that the amplitude of the variability appeared to be as large or greater than that in the observations (**Figure 22**). In addition, the phase speed of the eastward propagation seemed to match the observations fairly well, except for the 64-level version of the coupled model that appeared to have a relatively slower propagation speed (although see EWP results below). For both the uncoupled and coupled simulations, the 64-level versions showed considerably more intraseasonal activity. Part of the improvement associated with the 64-level versions was associated with an improvement in the mean state of the large-scale circulation, namely the tropical large-scale divergent flow.





**Figure 22.** Equatorial time-longitude diagrams of unfiltered 200 hPa velocity potential anomalies for the years 1994-1998 from CDAS (top) and from simulations using specified, observed SSTs using a 28-level (middle) and 64-level (bottom) version of the NCEP GFS. Units are  $1 \times 10^7 \text{ m}^2/\text{s}$ .

A more quantitative assessment of the propagation characteristics involved applying the EWP technique described above to equatorial 200 hPa velocity potential anomalies from the model simulations and comparing it to the result from observations. The results of this analysis showed that while the observed MJO, as exhibited by EWP, propagates at about 8 m/s and had an amplitude of about  $5 \times 10^6 \text{ m}^2/\text{s}$ , the models described above typically had propagation speeds of about 6-7 m/s and amplitudes of about  $5-7 \times 10^6 \text{ m}^2/\text{s}$ . In addition, to the above, results were shown regarding the models' ability to simulate the character of the major modes of atmospheric subseasonal variability (e.g., PNA, AO). The emphasis on these features stems from the fact that these contain a significant amount of autocorrelation (**Figure 23**) that needs to be properly represented and exploited in order to make progress on the subseasonal prediction problem. In some cases, the models' variability of these patterns was somewhat realistic (e.g., PNA, NAO), in other cases less so (e.g., AO), and in some cases highly unrealistic (e.g., QBO).



*Figure 23. Time-lagged autocorrelations of a number of indices of large-scale atmospheric variability computed from daily analysis data from June 6 2001 to June 2 2003.*

### III. Discussion and Recommendations

The presentations and discussions associated with this workshop were framed around three general themes: 1) the assessment and improvement of the representation of the MJO in our climate and forecast models (Section II.B), 2) the development of an implementation plan for an experimental MJO prediction program (Section II.C), and 3) the development of a framework for producing an ensemble of subseasonal predictions from a number of state-of-the-art forecast models in order to establish a baseline capability in the area of subseasonal prediction, provide a resource for follow-on activities associated with theme 1), and provide forecast climatologies, where applicable, for models participating in theme 2) (Section II.A).

In regards to the MJO modeling theme, there were a number of presentations that offered some optimism in regards to recent or current progress on the MJO modeling problem. These included particular parameterization tuning, impact of coupling, the so-called super-parameterization, identification of important basic-state interactions, and even implications from idealized studies. Aside from the individual modeling group efforts and results, it should be stressed that the fact that an MJO modeling workshop was held at all is an important sign of the recognition of the problem and the interest by the community to address it in some coordinated fashion. It was recommended that such workshops continue and that if possible an established working group be put together to coordinate activities in this area. This working group and associated workshops would be an important pathway for communication between the various model development teams, individual MJO research, and observation/satellite programs that can

lend important information to this effort. In addition, it was recommended that rectifying the MJO problem would necessarily rely on model experimentation activities such as the proposed subseasonal hindcasts, AMIP and targeted AMIP-like studies, as well as even more idealized modeling scenarios.

The experimental MJO prediction project received a great deal of support and enthusiastic participation from a number of PIs and forecasting agencies, including a number of international participants. Once developed, this project will allow the community to take advantage of the potential skill in forecasting the MJO that is present now, and that will hopefully increase in the near-future, as well as lend a modeling resource to those trying to remedy MJO simulation problems or diagnose interactions between the MJO and other aspects of weather and subseasonal variability (e.g., PNA, AO). The most notable issues discussed in regards to implementing this project included how to deal with forecast models that have yet or routinely do not have a lead-dependent forecast climatology which is necessary to remove a model's systematic biases, the degree that coupled models and ensembles need to be or can be incorporated into the project, the manner the MJO signal(s) are to be extracted from the heterogeneous set of models (e.g., empirical and numerical), and of course the general logistical problems of dealing with assembling a very non-uniform set of forecast products from different agencies and PIs in near real-time and streamlining them for the purpose of this project. Since the workshop, the project has entered into a preliminary implementation phase at CDC/NOAA and expectations are that a useful version of the project, containing a number of empirical and numerical forecasting contributions, will be forthcoming in months (<http://www.cdc.noaa.gov/map/images/mjo/>). It should be stressed that all efforts in regards to this project to date, both from the data host/server and the contributors, are either in-kind or based on funding that has not been augmented as yet to specifically facilitate/support this effort.

Finally, great progress was made at refining a framework for the subseasonal hindcast experiment. As this project is rather computationally intensive, the main issues to weigh were the relative benefits of frequent sampling of initial conditions (e.g., every 5 or 10 days), time period over which hindcasts were to be performed (e.g., previous 10 or 20 years), and the length of the hindcasts. After significant discussion, the proposed framework sought to accommodate a balance between these issues and accomplish something that could easily be augmented in the future with extensions of the experiment. One of the most problematic issues that arose was what to do in regards to the SST boundary conditions. Presentations in Session II.B indicated that any specification other than some form of coupled SST would be erroneous to some degree, at least concerning the proper representation of the MJO during the hindcast. However, having all participants perform coupled hindcasts is presently too burdensome and thus specification of some sort of forecast SST (TBD), was chosen. The initialization of the atmosphere raises two issues: 1) the model's systematic bias relative to the observed (or analyzed) state and the subsequent model adjustment this incurs, and 2) how to choose perturbation initial conditions for the ensemble members. The former is probably more of an issue in post processing and interpretation of the results while the latter has more to do with providing some form of uniformity across the models and adequately sampling the uncertainty of the initial conditions. Finally, one notable initialization problem concerns the hydrologic state of the land for which the community sorely lacks global, uniformly sampled, robust observations from which to work with. It is hoped that upcoming satellite missions (e.g., Hydros) may help to remedy this problem for future efforts along this line.

## Acknowledgements

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# Appendix I – List of Invitees/Participants

Themes:

1: General subseasonal modeling activity

2: Experimental prediction program

3: MJO modeling problem

NAME	INSTITUTE	COUNTRY	THEME	Response	Attended
Agudelo, Paula	Georgia Tech	USA			yes
Alves, Oscar	BMRC	Australia	2	y	
Amador Astua, Jorge	U Costa Rica	Costa Rica	1,2	y	yes
Arkin, Phil	UMD -ESSIC	USA	1	y	yes
Atlas, Bob	NASA/GSFC	USA	1		
Bacmeister, Julio	GSFC	USA	3	y	yes
Bamzai, Anjuli	NOAA/OGP	USA	1-3	y	yes
Bosilovich, Mike	GSFC	USA	1	y	yes
Branstator, Grant	NCAR	USA	1,3	y	yes
Busalacchi, Tony	UMD -ESSIC	USA		y	yes
Cai, Ming	UMD	USA	1	y	yes
Chang, Simon	ONR	USA			
Chang, Yehui	NASA/GSFC	USA	1	y	yes
Chen, Dehui	CMA	China	3		
Cocke, Steve	FSU	USA	1	y	yes
Collins, Dan	Georgia Tech	USA			yes
Davey, Mike	UKMO	England	2		
DelSole, Tim	COLA	USA	1	y	yes
DeWitt, Dave	IRI	USA	3	y	yes
Dirmeyer, Paul	COLA	USA	1	y	yes
Dole, Randall	NOAA/CDC	USA	1-3	y organizer	yes
Donner, Leo	GFDL	USA	3	n	
Einaudi, Franco	NASA/GSFC	USA			
Emanuel, Kerry	MIT	USA	3		
Fan, Yun	NOAA/CPC	USA			yes
Fein, Jay	NSF	USA		y	
Feldstein, Steve	PSU	USA	1		
Flatau, Maria	NRL/FLEET	USA	2	y	yes
Fu, Xiouhua	IPRC/SOEST	USA			
Gao, Xiang	COLA	USA			yes
Goddard, Lisa	IRI	USA	1		
Graham, Richard	UKMO	England			
Guo, Zhichang	COLA	USA			yes
Gutzler, Dave	UNM	USA	1	n	
Hack, James	NCAR	USA	1,3		
Held, Isaac	GFDL	USA	3		
Helfand, Mark	NASA/GSFC	USA	1,3	y	yes
Hendon, Harry	BMRC	Australia	2	n	
Higgins, Wayne	NCEP/NOAA	USA	2	y	yes
Hoyos, Carlos	Georgia Tech	USA			yes
Hou, Arthur	NASA/GSFC	USA	1	y	yes
Houser, Paul	NASA/GSFC	USA	1		
Huang, Jin	NOAA/OGP	USA	1		

Inness, Peter	U Reading	UK	2-3	y	yes
Iredell, Mark	NOAA/NCEP	USA	3	y	
Ji, Ming	NOAA/OGP	USA		y	yes
Johnson, Donald	UW Madison	USA	1		yes
Jones, Charles	UCSB	USA	2	y	yes
Jung, Hyun-Sook	KMA	Korea	1,2	y	yes
Kalnay, Eugenia	UMD	USA	1	y	yes
Kanamitsu, Masao	SIO	USA	1	y	yes
Kang, In-Sik	SNU	Korea	2,3		
Kar, S.C.	NCMRWF	India	3	y- travel	yes
Khairoutdinov, Marat	CSU	USA	3	y	yes
Kim, Hyun-Kyung	NCEP/RSIS	USA			yes
Kim, Kyu-Myong	SSAI	USA			yes
Kinter, James	COLA	USA	1-3		yes
Kirtman, Ben	COLA	USA	1		yes
Koster, Randy	GSFC	USA	1	y	yes
Krishnamurti, T.N.	FSU	USA	1-3	y	
Kumar, Arun	CPC/NCEP	USA	1	y organizer	yes
Kushner, Paul	GFDL	USA	1	y	
Larow, Tim	FSU	USA	1	y	
Lau, Bill	GSFC	USA	1-3	y	yes
Lau, Gabriel	GFDL	USA	1,3		
Laver, Jim	NCEP/NOAA	USA	1-3	y	
Lawford, Richard	NOAA/OGP	USA	1		
Lee, Myong-In	GSFC	USA	1,3	y	yes
Lee, Tsengdar	NASA HDQTRS	USA		y	
Legler, David	CLIVAR	USA		y	yes
Li, Tim	IPRC/SOEST	USA		y	yes
Liess, Stefan	SUNY	USA	2,3	y	yes
Lord, Steve	NCEP/NOAA	USA	1-3	y	
Maloney, Eric	OSU	USA	3	y-travel	yes
Mather, Jim	PNNL	USA	1	y	yes
Mechoso, Roberto	UCLA	USA	1		
Min, Dughong	COLA	USA			yes
Mo, Kingste	CPC/NOAA	USA	2	y	yes
Moorthi, Srinivas	NCEP/NOAA	USA	3	y	yes
Neelin, David	UCLA	USA	3		
Neff, Bill	ETL/NOAA	USA	1,3	y	yes
Newman, Matt	CDC/NOAA	USA	1,2	y	yes
Nigam, Sumant	UMD	USA	1		
Pan, Hua-Lu	EMC//NOAA	USA	3	y	yes
Park, C.K.	KMA	Korea	2	y - travel	yes
Patterson, Michael	NOAA/OGP	USA	1-3		
Pegion, Kathy	George Mason	USA	1	y	yes
Pegion, Phil	GSFC	USA	1	y	yes
Pena Mendez, Malaquias	UMD	USA			yes
Peng, Peitao	NOAA/CPC	USA			yes
Ralph, Marty	ETL/NOAA	USA	1,3	y	yes
Randall, Dave	CSU	USA	3	n	
Raymond, Dave	UNM	USA	3		

Rienecker, Michele	GSFC	USA	1	y	
Saha, Suranjana	EMC/NOAA	USA	1	y	yes
Sardeshmukh, Prashant	CDC/NOAA	USA	1,3		
Schemm, Jae	NCEP/NOAA	USA	1, 3	y	yes
Schneider, Ed	COLA	USA	1	y	yes
Schubert, Siegfried	NASA/GSFC	USA	1-3	y organizer	yes
Seo, Kyong-Hwan	NCEP/NOAA	USA	1	y	yes
Shuka, J.	COLA	USA	1-3	y	yes
Singh, S.V.	NCMRWF	India	3		
Slingo, Julia	U.Reading	UK	1,3		
Sperber, Ken	LLNL	USA	1-3	y	yes
Stern, Bill	GFDL	USA	1,3	y	yes
Straus, David	COLA	USA	1	y	yes
Suarez, Max	GSFC	USA	1,3	y	yes
Sud, Yogesh	GSFC	USA	2	y	yes
Sugi, Masato	JMA	Japan	2		
Todd, James	NOAA/OGP	USA	1		
Toth, Zoltan	NCEP/NOAA	USA	1	y	yes
Tracton, Steve	ONR	USA	1-3	y	
Tribbia, Joe	NCAR	USA	1	n	
Van den Dool, Huug	NCEP/NOAA	USA	1,2	y	yes
Van Pelt, Derek	GSFC/NASA	USA	3	y	yes
Vitart, Frederic	ECMWF	Europe	1,2	y -travel	yes
Waliser, Duane	SUNY	USA	1-3	y organizer	yes
Wallace, Mike	U. Washington	USA	1		
Wang, Bin	UH	USA	3	y	yes
Wang, Wanqui	NCEP/NOAA	USA	3	y	yes
Webster, Peter	Georgia Tech	USA	1-3	n	
Weickmann, Klaus	CDC/NOAA	USA	1,2	y	yes
Wheeler, Matt	BMRC	Australia	2	y - travel	yes
Whitaker, Jeff	CDC/NOAA	USA	1	y	yes
White, Glenn	EMC/NOAA	USA	1,2	y	yes
Wu, Man Li	GSFC	USA	1-3	y	yes
Xue, Yan	NOAA/CPC	USA	3	y	yes
Yang, Fanglin	GEST/UMBC	USA	2	y	yes
Yang, Song	GSFC/NASA	USA	1	y	yes
Zhang, Chidong	U Miami	USA	1-3	y	yes
Zhang, Qin	NOAA/CPC	USA			yes
Zhang, Renhe	CMA	China	3		
Zhao, Mei	COLA	USA			yes
Zhou, Jiayu	NOAA/NWS/OST	USA	1-3	y	yes
Zwiers, Francis	CCCMA	Canada	1		

## Appendix II – Workshop Invitation

3/17/03

Dear Colleague,

We would like to invite you to attend a planning workshop on "Modeling, Simulation and Forecasting of Subseasonal Variability" to be held on 4-5 June 2003, in Greenbelt, Maryland. The workshop is meant to serve as a follow-up meeting to the NASA-sponsored workshop entitled "Prospects For Improved Forecasts Of Weather And Short-Term Climate Variability On Sub-Seasonal Time Scales" that was held last April. The overarching objective is to set an agenda and collate efforts in the areas of modeling, simulation and forecasting intraseasonal and short-term climate variability.

The April workshop<sup>5</sup> highlighted a number of key sources of unrealized predictability on subseasonal time scales including tropical heating, soil wetness, the Madden Julian Oscillation (MJO)/Intraseasonal Oscillation (ISO), the Arctic Oscillation (AO) and the Pacific/North American (PNA) pattern. This workshop is envisioned as the first of a number of follow-up planning meetings to 1) develop a baseline of the "state of the art" in subseasonal prediction capabilities, 2) carry out experimental forecasts, and 3) develop strategies for tapping the above sources of predictability by focusing research, model development, and the development/acquisition of new observations on the subseasonal problem.

In this workshop, we will focus the agenda on issues related to the MJO and tropical-extratropical interactions as they relate to the subseasonal simulation and prediction problem. This includes the development of plans for a coordinated set of GCM hindcast experiments to assess current model subseasonal prediction capabilities and shortcomings, an emphasis on developing a strategy to rectify shortcomings associated with tropical variability, namely diabatic processes, and continuing the implementation of an experimental forecast and model development program that focuses on one of the key sources of untapped predictability namely the MJO. Specifically, the objectives are threefold:

- 1) Develop the framework for a set of multi-decade ensembles of 60-90 day hindcasts from a number of GCMs so that they can be analyzed in regards to their representations of subseasonal variability, predictability and forecast skill. This includes any/all subseasonal phenomena (e.g., AO, PNA, MJO) and their associated tropical-extratropical interactions. The focus here is on addressing such issues as ensemble size, initial conditions, boundary conditions, and the seasonality and longer-term variability of subseasonal forecast skill. We encourage you to also consider proposing possible "case studies" that would help to assess the impact of observations or sensitivity to model formulation, as well as empirical studies that could serve as benchmarks for the GCM simulations.
- 2) Develop an agenda and modeling/simulation work plan to address shortcomings associated with tropical variability, with a particular emphasis on remedying the shortcomings associated with GCM representations of the MJO. Here we especially encourage the different modeling groups to summarize their experience in attempting to improve the representation of the MJO
- 3) Continue the development of the multi-institute/multi-nation Experimental MJO Prediction Program that is taking foot with the help of the NOAA Climate Diagnostics Center (CDC). The proposed workshop will provide a mechanism to gather the participants to discuss the completion of the experimental prediction framework and its implementation.

Please respond no later than April 18 if you plan to attend, though we encourage you to let us know as soon as possible so that we can better estimate our lodgings requirements. Detailed information on travel

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<sup>5</sup> Summary available at: <ftp://anonymous@nsipp.gsfc.nasa.gov/pub/abstracts/abstractsfinalprint.pdf>

and other logistical information will follow. The workshop is sponsored by the U.S. CLIVAR program, with funding provided by NASA, NOAA and NSF. A limited amount of travel support is available.

Sincerely,

The organizing committee:  
Siegfried Schubert <siegfried.d.schubert@nasa.gov>  
Duane Waliser <duane.waliser@sunysb.edu>  
Randy Dole <Randall.M.Dole@noaa.gov>  
Arun Kumar <Arun.Kumar@noaa.gov>

Note: Please cc your response to Nefertari Johnson  
<nefertari.johnson@gsfc.nasa.gov>

# Appendix III – Workshop Agenda

**Day 1:** The first day is devoted to the development of plans for producing a baseline set of model and other empirical/hybrid hindcast experiments to assess our current prediction capabilities at subseasonal time scales. There will be a number of short talks (approx 10 minutes) to help motivate and focus the discussions. You are also invited to bring your own favorite view graphs to help with the discussion, but please keep in mind that this is a planning workshop so we are not looking for in-depth science discussions.

## Morning

### 1) Introduction and overview (8:30am)

- NASA – TBD (5 min)
- NOAA – Ming Ji (5 min)
- CLIVAR – David Legler (5 min)

Overview – S. Schubert

- Motivation and goals
- Results and Recommendations of first workshop
- Related global model assessment efforts (AMIP, SMIP, etc)

### 2) Proposal for baseline AGCM hindcasts (9:00am) Chair: Shukla

- a. Ensemble size, period, frequency, length, etc.
- b. Specification of initial and boundary conditions
  - i. Atmospheric ICs: (J. Whitaker)
  - ii. Land ICs: (P. Dirmeyer)
  - iii. SST/sea ice specification (H. van den Dool, D. Waliser)

**Break** (10:00-10:30)

**Lunch** (12:00-1:00pm)

## Afternoon

### 3) Additional model experiments (1:00pm) Chair: E. Kalnay

- a. Atmosphere
  - i. Sensitivity to reanalyses
  - ii. Precipitation assimilation (E. Kalnay, A. Hou)
- b. Land
  - i. Role of land/atmosphere coupling (R. Koster)
- c. Ocean
  - i. Coupled Ocean versus specified SST (F. Vitart, S. Saha, M. Pena)
  - ii. Ocean mixed layer experiments (W. Lau)
- d. Other
  - i. Coupled AMIP (M. Cai)
  - ii. Hybrid/idealized forcing experiments

**Break** (2:45-3:15)

### 4) Empirical/statistical methods and postprocessing (3:15pm)

Chair: H. van den Dool

- a. Baseline statistical predictions for assessing AGCMs
  - b. Understanding AGCM results using simpler models
    - i. LIM- M. Newman
  - c. Improved estimates of PDFs through postprocessing
    - i. J. Whitaker
- 5) **Data sharing** (5:00-5:30pm) – Chair: TBD
- a. Minimal set of output quantities
  - b. Centralized/decentralized storage

## **Day 2:**

### **Morning: MJO Modeling & Simulation: Rectifying Shortcomings**

- 1) Introduction  
8:30-8:35: Duane Waliser
- 2) Short Overviews: Present Status and Shortcomings  
8:35-8:50: MJO in N.H. Winter – Ken Sperber – AMIP/MJO Study  
8:50-9:00: MJO in N.H. Summer – Duane Waliser – CLIVAR Study  
*This is designed to highlight the main successes and shortcomings for the models in general when compared to observations.*
- 3) Short Reviews & Discussion: Modeling Efforts (Chair: Ken Sperber)  
*These reviews are to describe specific efforts to improve the MJO simulations by individuals or modeling groups, and/or give reports of MJO sensitivity to various model changes. This item is meant to help guide the discussion in item 4 by noting specific examples of success, failure and/or ambiguity.*  
9:00-9:15: GSFC – Julio Bacmeister  
9:15-9:30: SNU – Myong-In Lee  
9:30-9:45: GFDL- Bill Stern  
9:45-10:00: OSU/NCAR – Eric Maloney

#### **Break 10:00-10:30**

- 10:30-10:45: CSU – D. Randall/M. Khairoutdinov
- 10:45-11:00: NCEP – Hualu Pan/Arun Kumar
- 11:00-11:15 – Matt Wheeler
- 11:15-11:30 – Bin Wang
- 11:30-11:45 – Pete Inness
- 11:45-12:00 – Zhaohua Wu

- 4) Roadmap to Rectifying MJO Shortcomings (Chair: Max Suarez)

12:00-12:30:

*This session is to reach a consensus on where we are with the MJO modeling problem, examine what efforts, if any, are presently underway that might help, examine observational needs and theoretical guidance, discuss the extent that MIPs vs coordinated model simulations would help, discuss the impact/relevance of the model mean state, air-sea coupling, heating profile, etc. Ideally, the outcome of this session will include the development of a future agenda to deal with this issue, possibly a focused working group and maybe a set of model experiments.*

### **Lunch 12:30-1:30**

### **Afternoon: MJO Experimental Prediction Program**

- 1) Background and Objectives

1:30-1:40: Duane Waliser

*This will involve a very brief background of how this experimental project got underway, what it involves and its overall objectives.*

- 2) Proposed Framework: Status of CDC/NOAA Efforts

1:40-2:10: Klaus Weickmann

*This will be an outline of the initial framework for the program, the progress made in regards to that framework, the outlook for completing and/or making modifications to the framework. This will involve introducing issues such as initial conditions, variables to examine, ensemble size if applicable, forecast lengths, post-processing, benchmarks from empirical models and validation from observations. Many of these issues will be discussed in item 4) below.*

- 3) Empirical Forecasts: Describe Available Products/Methods

*The idea behind hearing from the Empirical modelers is that in each case, their models are relatively unique and only supply a certain set of predictors – as opposed to the NWP models which can all roughly supply the same large set of predictors. Since these models will likely be useful benchmarks for predictive skill, it is useful to know what they will have to offer in that regard.*

2:10-2:20: Matt Wheeler

2:20-2:30: Charles Jones

2:30:2:40: Matt Newman

2:40-2:50: P. Webster/D. Collins/C. Hoyos

2:50-3:00 Suranjana Saha

**Break 3:00-3:15**

- 4) Consensus on Framework/Products/Contributions (Chairs: Klaus Weickmann and Duane Waliser)

*3:15-4:15: In this session, each forecast group/agency will need to describe what products they have already that work within the context of the proposed framework and/or that could be developed/provided. It is expected that the discussion will likely lead to modifications to the proposed framework.*

- 5) Workshop Wrap-Up: Future Plans/Agenda/Links to CCSP

4:15-4:30: Organizing Committee

## Appendix IV – Experimental Prediction Invitation

November 7, 2002

Dear Colleague,

This last April, a workshop entitled *Prospects For Improved Forecasts Of Weather And Short-Term Climate Variability On Sub-Seasonal Time Scales* was held in Mitchellville, Maryland. The goals of the workshop were to get an assessment of the “state of the art” in predictive skill on time scales of 2 weeks to 2 months, to determine the potential sources of “untapped” predictive skill, and to make recommendations for a course of action that will accelerate progress in this area. One of the key conclusions of the workshop was that there is compelling evidence for predictability at forecast lead times substantially longer than two weeks, with some part of this predictability stemming from tropical intraseasonal variability, namely the Madden-Julian Oscillation (MJO; a.k.a. Intraseasonal Oscillation). In fact, one of the key recommendations (see enclosed workshop proceedings) was that “...a coordinated multi-nation/multi-model experimental prediction program be developed focused on the MJO.” Following the workshop, a somewhat lengthy email discussion developed between a number of the workshop participants and other MJO enthusiasts to try and address/fulfill this recommendation. Through this discussion, a preliminary framework for this experimental prediction program was developed (see attached framework description). In addition, through a combination of solicitation and good will, it was determined that the NOAA Climate Diagnostics Center (CDC) would be willing to sponsor the project in terms of being the data repository for the forecasts, performing some nominal analyses, and serving the data to the community via the web. These two events, the development of the program framework and the identification of a sponsor, provide the basis for moving forward with this exciting initiative and thus are the basis for this invitation letter.

Due to your interest and expertise in the areas discussed above, we are writing to inform you of this project and invite you and/or your agency’s participation. Our hope is to have a number of empirical and dynamical tropical prediction products included in this experimental program. Given that the sub-seasonal time scale is a relatively new, and certainly challenging, area of prediction, particularly in the tropics, our initial expectations regarding skill for these forecasts are not overly optimistic. Thus, we hope your consideration of whether to participate will be dictated as much or more by general interest in tropical weather/climate prediction and the long-range goals of this experimental program rather than the current perceived tropical forecast skill of your or your agency’s model. In addition, when reviewing the enclosed program framework and request for data keep in mind that this is a “wish list” and we understand that not all forecasts and/or forecast centers would be able to comply with all these data parameters (e.g., 30-day lead). Finally, after reviewing this letter and its contents, please feel free to pass this invitation letter on to who ever you think is appropriate in regards to determining the level at which you or your agency can participate. Moreover, if you would like us to send an invitation letter to someone in particular, either within your agency or to another agency/person that you think might be interested, please feel free to make such a recommendation.

Thank you for considering our invitation and don’t hesitate to contact us in the event you have questions, comments or suggestions.



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## Long-lead Tropical/MJO Experimental Prediction Program Data and Prediction Framework

As mentioned in the invitation letter, the following framework is meant only meant to serve as a guide. Given the different priorities and capabilities of the each forecast center and modeler, it is understood that not every participant will be able to comply with all aspects of the proposed framework. Moreover, it is expected that an individual dialogue will be developed between each participant and the CDC sponsors to discuss the details regarding what forecast data is available, what aspects of forecast data post-processing need to be undertaken by the participant versus CDC, the mechanism for transferring the data, etc. The framework includes two forecast data streams: one for tropical variability in general and one that is specific to the MJO and related sub-seasonal variability. While this experimental prediction program is mainly focused on the latter, there is still considerable interest and utility in understanding how models are performing at shorter time scales. Specifically, an understanding and assessment of a model's performance at these shorter time scales (e.g., weather) may be helpful in interpreting the model's capabilities and shortcomings at the longer intraseasonal time scale. In addition, it is understood that not all forecast centers/systems produce extended-range predictions with a long enough lead such that some form of filtering can be effectively applied to isolate the coherent intraseasonal modes (e.g., MJO) and/or to make useful predictions over their characteristic time scale (e.g., 50 days).

**FORECAST "STREAMS":** a) MJO-associated anomalies, and b) TOTAL field (with a model climatology supplied if applicable).

**VARIABLES:** U200, U850, V850, rainfall, OLR, VP200, SF200

**TIME RESOLUTION:** Daily, from day -10 to day +30<sup>6</sup>, where day 0 is the last day of the observed data in the forecast system. Daily resolution will allow our CDC sponsors to later do averaging into 5-day means or 7-day means for any chosen 5- or 7-day period. In the event an empirical scheme produces 5-day mean values, then the output of the scheme should be interpolated to daily before it is sent to CDC. Sending daily data will allow better comparison between forecast products that will have different initial condition (day 0) times. Data from day -10 to day 0 will be used for some simple filtering schemes to better isolate the MJO and related modes.

**UPDATE FREQUENCY:** Every 1, 5 or 7 days. Yet to be determined.

**GRID:** 2.5° grid global fields.

**ENSEMBLES:** It is hoped that in the case of numerical predictions that ensemble predictions can be made available.

**DISPLAY PRODUCTS:** This is mostly up to the CDC sponsors, but it is likely to include. 1) maps of forecasted 5- or 7-day means, and 2) time-longitude plots out to lead times of up to 30 days for various latitude bands. In addition, depending on the resources available to CDC for this project, aggregate measures of forecast skill may also be computed and displayed.

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<sup>6</sup> If you or your agency have the means to produce longer lead forecasts (e.g., 60 days), please inform us of this capability so we can assess the practicality of extending this limit.

## List of Invitees

The list below is not exhaustive nor meant to be exclusive. It is simply an initial list of forecast agencies and empirical modelers that were thought to have the potential and interest for providing a useful contribution to the project. If you have any suggestions for other invitees, please provide them to Duane or Klaus.

Forecast Agency	Country	Initial Contact(s)
NCEP/NOAA	USA	Huug van den Dool
NASA/GSFC	USA	Siegfried Schubert
COLA	USA	J. Shukla / James Kinter
JMA	Japan	Masato Sugi / Nobuo Sato
CMA	China	Renhe Zhang / Dehui Chen
KMA	Korea	C.K. Park / In-Sik Kang
ECMWF	Europe	Tim Palmer / Frederic Vitart
UKMO	England	Richard Graham / Mike Davey
NRL/FLEET	USA	S. Chang / T. Hogan/C. Reynolds/M. Flatau
BMRC	Australia	Oscar Alves
GFDL	USA	William Stern
NCMRWF	India	S.V. Singh / S.C. Kar

Empirical Modelers	Country	Institute
Matt Wheeler	Australia	BMRC
Harry Hendon	Australia	BMRC
Charles Jones	USA	UCSB
Kingste Mo	USA	NCEP/NOAA
Wayne Higgins	USA	NCEP/NOAA
Matt Newman	USA	CDC/NOAA

# **Appendix V – MJO Experimental Prediction Framework**

## 1. Forecast "Streams"

Our interest here is to have forecasts of total values and anomaly values – and then some index or quantity that represents the MJO activity more specifically. The main issue here is whether GCM participants can compute anomalies and, if so, what climatology they have available to do so. CDC computes anomalies for its "MRF" ensemble from our reforecast dataset as a function of forecast lead-time. While this might be considered optimal, a reforecast dataset is not typically available at operational centers. NCEP/CPC is using the NCEP reanalysis to compute anomalies for its GFS ensemble predictions. This is a reasonable alternative if no other climatology is available. Systematic model error then becomes part of the forecast anomaly. The issue of how to extract the MJO from the total anomaly is still uncertain at this point. Matt Wheeler showed an approach based on projection of anomalies on two combined EOFs of observed data. The variables included in the EOFs are 200 mb and 850mb zonal wind and OLR. Matt has sent CDC his EOFs and as an initial test we propose to project the predictions onto these to extract the MJO. Since we are after the observed MJO and not a model's version, this seems like a reasonable first step.

The statistical models generally predict anomalies, and some predict only those associated with the MJO. We will still need to know what climatology is being used to make anomalies.

## 2. Variables (global grids preferred)

- a. u, v fields at 200 mb, 850 mb and the surface, 200 mb streamfunction and velocity potential would also be helpful to minimize CDC's computational load.
- b. 500 mb heights - to compute major subseasonal indices and monitor extra-tropical MJO impacts.
- c. rainfall, OLR, column average total diabatic heating: it is understood that not all of these will be available from everyone.
- d. sea surface temperatures, with an indication of whether these are based on a numerically coupled model, an empirical model, etc.

## 3. Time resolution, forecast length and update frequency

These will be quite variable. We would prefer: daily resolution, 30 day (or more) forecast length, and an update frequency of at least every five days. However, it is acknowledged that not all agencies will be able to accommodate these specifications, so we will take what we get.

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