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The 1st Pan-WCRP Workshop on Monsoon Climate Systems: Toward Better Prediction of the Monsoons

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Executive Summary

a. Introduction and Motivation

In 2004 the Joint Scientific Committee (JSC) that provides scientific guidance to the World Climate Research Programme (WCRP) requested an assessment of (1) WCRP monsoon related activities and (2) the range of available observations and analyses in monsoon regions. The purpose of the assessment was to (a) define the essential elements of a pan-WCRP monsoon modeling strategy, (b) identify the procedures for producing this strategy, and (c) promote improvements in monsoon observations and analyses with a view toward their adequacy, and addressing any undue redundancy or duplication. As such, the WCRP sponsored the "1st Pan-WCRP Workshop on Monsoon Climate Systems: Toward Better Prediction of the Monsoons" at the University of California, Irvine, CA, USA from 15-17 June 2005. Experts from the two WCRP programs directly relevant to monsoon studies, the Climate Variability and Predictability Programme (CLIVAR) and the Global Energy and Water Cycle Experiment (GEWEX), gathered to assess the current understanding of the fundamental physical processes governing monsoon variability and to highlight outstanding problems in simulating the monsoon that can be tackled through enhanced cooperation between CLIVAR and GEWEX. The agenda with links to the presentations can be found at:

http://www.clivar.org/organization/aamon/WCRPmonsoonWS/agenda.htm

Scientific motivation for a joint CLIVAR-GEWEX approach to investigating monsoons includes the potential for improved medium-range to seasonal prediction through better simulation of intraseasonal (30-60 day) oscillations (ISO's). ISO's are important for the onset of monsoons, as well as the development of active and break periods of rainfall during the monsoon season. Foreknowledge of the active and break phases of the monsoon is important for crop selection, the determination of planting times and mitigation of potential flooding and short-term drought. With a few exceptions simulations of ISO are typically poor in all classes of modeling. Observational and modeling studies indicate that the diurnal cycle of radiative heating and surface fluxes over the ocean are rectified on to the intraseasonal timescale indicating that a synergistic approach to studying monsoon variability is necessary. The diurnal cycle of precipitation and clouds, which directly influence the radiative heating and surface fluxes, are also poorly represented in global models, especially. Thus, it is anticipated that improving the simulation of the diurnal cycle of precipitation and clouds in global models will contribute to an improved ability to simulate ISOs. Improved understanding and simulation of the diurnal cycle is also important since it influences low-levels jets and the associated transport of moisture as well as the rainfall over regions of complex topography.

b. Workshop Structure

The workshop consisted of three main sessions: (1) "Key modeling issues and observational requirements" which was dominated by presentations from CLIVAR panels and GEWEX efforts to observe, understand, model, and predict the Earth's monsoon systems, (2) "Invited presentations: Fundamental physics and dynamics of monsoon" during which invited presentations were given on (a) Dynamics of seasonal cycle and intraseasonal variations, (b) Role of air-sea interaction, (c) Boundary layer and low-level jets, (d) Role of land processes and fluxes, (e) Role of diurnal cycles of heating and convection, (f) GEWEX Cloud System Studies-activities and parameterization development for monsoon prediction, (g) Cloud/precipitation processes and cumulus parameterization for monsoon modeling, (h) Regional modeling of monsoons, (i) Predictability and prediction of monsoons, and (j) Modeling and Predictability Efforts, and (3) "Working Group Breakouts" to evaluate (i) Strategy for parameterization development and observational data requirements, (ii) Strategy for system modeling and observational data for large-scale model validation, and (iii) Monsoon prediction and the required monitoring network. This was followed by a plenary session at which the three breakout groups presented their recommendations for future activities.

c. Science Recommendations

- Improve the simulation of the diurnal cycle of precipitation and convection in global models. This will be achieved by making use of regional climate models and cloud-resolving models that have more comprehensive physics. This is the primary near-term goal that will crosscut the expertise of CLIVAR and GEWEX.
- Improved modeling of intraseasonal oscillations, which affect large-scale convection in the tropics on a time scale of ~30-70 days. Closer cooperation between CLIVAR, GEWEX, and CAPT activities may lead to a better understanding and improved modeling of the ISO (irrespective of the possible improvement in ISO that may arise to better simulation of the diurnal cycle of clouds and convection).
- Perform more process studies and modeling of the Maritime continent and the Indian Ocean.
- Achieve a better understanding of the atmospheric moisture distribution and transport.
- Improved representation of the planetary boundary layer, including an integrated approach to evaluating physics parameterizations and their interactions.
- Sensitivity testing to determine the resolution necessary in global models to simulate multi-scale interactions that dominate the Earth's monsoon systems.
- In regional climate models (RCMs) a better understanding is needed of the limitations imposed by having to specify lateral boundary conditions. Alternative nesting techniques, such as two-way nesting, need to be explored. This may help in understanding scale interactions across the different resolved spatial scales.
- Achieve greater fidelity in the simulation of the equatorial cold tongue in the Pacific Ocean, the sea surface temperature in the tropical Atlantic Ocean, and the western boundary currents.
- Improved (and sustained) observations are needed over sparsely sampled regions of the tropical oceans, especially the Indian Ocean.
- The role of land-atmosphere coupling needs to be benchmarked against observations.
- Better observations of land surface conditions are needed (e.g., soil moisture, snow cover, snow depth) for understanding processes, and because these quantities can serve as boundary conditions for model simulations.
- The role of aerosol and dust and its impact on the development of monsoon precipitation should be investigated, though at present these may be secondary to errors in the basic structure of monsoon simulations.
- The importance of air-sea interaction for modulating intraseasonal variability and for capturing the monsoon-ENSO teleconnection suggests that use of coupled ocean-atmosphere models is a key requirement for monsoon prediction.

d. Barriers to Progress

- The decay of the observational network needs to be reversed, with the network expanded into regions where observations are scant.
- Raise the profile of model and parameterization development. This calls for a sustained funding commitment from agencies.
- Lack of adequate computer facilities for the sensitivity testing to understand complex processes and their feedbacks. Testing the spatial resolution and temporal resolution and physics dependencies should be considered a "Grand Challenge" problem to the modeling community in terms of scientific effort and computing.

e. Implementation Mechanisms

- Establish a Pan-WCRP monsoon panel/working group within the COPES initiative.
- Hold targeted workshops to foster interaction for sustaining CLIVAR and GEWEX interactions. These can be held in conjunction with existing panel meetings, as sessions at conferences, or independently. The first will be focused on the diurnal cycle over ocean and land.

- Continue the process, started at the workshop, of building of an agreed list of priorities that could be facilitated by Pan-WCRP interactions.
- Develop a joint CLIVAR-GEWEX approach to the Asian-Australian monsoon, building on the current CLIVAR-GEWEX collaboration on the American and African monsoon systems.

f. Members of the Scientific Organizing Committee

T. Yasunari (co-chair)

K. R. Sperber (co-chair)

W. Higgins

W. K.-M. Lau

J. McCreary

C. R. Mechoso

J. Polcher

K. Puri

J. Slingo

C. Thorncroft

B. Wang

G. Wu

1. Introduction and Motivation

The Earth's monsoon systems are the life-blood of more than two-thirds of the world's population through the rainfall they provide to the mainly agrarian societies they influence. In some cases the monsoon is remarkably regular, for example over India the interannual standard deviation of the rainfall is about 10% of the annual mean, but the perturbations are strong enough to lead to natural disasters resulting from flood or drought and the associated land-use impacts. During the course of the monsoon season there can also be strong variations in rainfall. Intraseasonal (30-60 day) variations (ISOs) influence the onset of the monsoon and give rise to protracted active (enhanced) and break (deficient) periods of rainfall. Foreknowledge of the active and break phases of the monsoon is important for crop selection, the determination of planting times and mitigation of potential flooding and short-term drought. Poor simulation of the ISO has been a pervasive problem in all scales of modeling. Though there are exceptions to this latter statement, attempts to translate "success" in simulating the ISO from one model to another have met with limited success at best. Additionally, the poor simulation of ISOs is a limiting factor for medium-range to seasonal forecasting. The success of empirical methods in forecasting intraseasonal variability indicates that there is skill to be gained through improved dynamical models. Observational and modeling studies indicate that the diurnal cycle of radiative heating and surface fluxes over the ocean are rectified on to the intraseasonal timescale indicating that a synergistic approach to studying monsoon variability is necessary. The diurnal cycle of precipitation and clouds, which directly influence the radiative heating and surface fluxes, are also poorly represented in global models, especially. Thus, it is anticipated that improving the simulation of the diurnal cycle of precipitation and clouds in global models will contribute to an improved ability to simulate ISOs. Improved understanding and simulation of the diurnal cycle is also important since it influences low-levels jets and the associated transport of moisture as well as the rainfall over regions of complex topography. Furthermore, from a physical standpoint, study and improved modeling of the monsoon is also important since the associated large-scale energy exchange due to the cycling of water vapor in the atmosphere is central to the development of the general circulation of the atmosphere.

Due to the potentially grave societal impacts of monsoon variability on numerous time scales and since modeling monsoons remains a challenge the World Climate Research Programme (WCRP) sponsored the 1st Pan-WCRP Workshop on Monsoon Climate Systems at the University of California, Irvine, CA, USA from 15-17 June 2005. The major goal of the workshop was to promote closer interaction between two WCRP projects, the Climate Variability and Predictability Project (CLIVAR) and the Global Energy and Water Cycle Experiment (GEWEX). This effort is part of a new WCRP strategic framework for Coordinated Observation and Prediction of the Earth System (COPES). More than 60 experts gathered to assess our current understanding of the fundamental physical processes governing monsoon variability and to highlight outstanding problems in simulating the monsoon whose alleviation can be helped by enhanced cooperation between CLIVAR and GEWEX. The urgent requirement of full coordination and cooperation of monsoon-related research activities between these two programs for better understanding and seamless prediction of the monsoon systems was the background to the proposal for the workshop. By necessity, due to the longer time scales considered, (CLIVAR based) global models that are used for sub-seasonal, interannual, and climate studies are coarser in resolution and less complex in terms of physical parameterizations than the (GEWEX based) regional and cloud resolving models that are used for diurnal to subseasonal studies. Closer cooperation between CLIVAR and GEWEX should provide the opportunity to improve global models by better understanding the important process in the regional and cloud resolving models that are responsible for their better simulations compared to global models. The meeting was chaired by Prof. Tetsuzo Yasunari and Dr. Kenneth R. Sperber.

To provide perspective regarding the CLIVAR and GEWEX efforts, a brief historical account of the WCRP and these two programs is given. The WCRP was established in 1980 under the sponsorship of the International Council of Science, and the World Meteorological Organization. Since 1993 it has also been sponsored by the Intergovernmental Oceanographic Commission. The goal of WCRP has been to improve our understanding of processes in the physical climate system needed to assess climate predictability, and to assess the degree to which anthropogenic influences may affect future climate. WCRP provides a framework for establishing international efforts for modeling and observing the climate system. The numerous successes of WCRP include (1) the Tropical Ocean Global Atmosphere (TOGA) project that has revolutionized our understanding of the El Nino/Southern Oscillation (ENSO) and its global impact, and has led to operational predictions of ENSO that have skill out to about one year, (2) the World Ocean Circulation Experiment (WOCE) that has provided much needed observations of the world oceans, improved our knowledge of oceanic physical processes, and has led to the development of advanced ocean observing systems, and (3) the Arctic Climate System Study (ACSYS) that has worked towards clarifying the role of the Arctic in the global climate system.

To build upon the success of TOGA and WOCE, WCRP initiated the Climate Variability and Predictability Project (CLIVAR) in the mid-1990s. The purpose of CLIVAR is "To describe and understand climate variability and predictability on seasonal to interannual time scales, identify the physical processes responsible, including anthropogenic effects, and develop modeling and prediction capabilities where practicable." The principal research areas include monsoons, tropical modes, extratropical modes, thermohaline circulations, and anthropogenic climate change. CLIVAR has three monsoon related panels: the Asian-Australian Monsoon Panel (AAMP), Variability of the African Climate System (VACS), and Variability of the American Monsoon Systems (VAMOS). In addition, the joint Global Ocean Observing System (GOOS)/CLIVAR Indian Ocean Panel has been developing an implementation plan for sustained ocean observations of the Indian Ocean region. A number of CLIVAR's monsoon-related activities are joint with GEWEX. The tendency overall is for CLIVAR efforts to concentrate on the slowly evolving component of the climate system, hence the emphasis of the oceans role in climate. Modeling efforts tend to concentrate on the global system using General Circulation Models (GCMs), and as such they tend to have coarse horizontal resolution (100's km).

WCRP established the Global Energy and Water Cycle Experiment (GEWEX) in the early 1990's in recognition of the need "to observe, understand and model the hydrological cycle and energy fluxes in the atmosphere, at the land surface and in the upper oceans." GEWEX research is coordinated through: (1) the GEWEX Radiation Panel (GRP), (2) the GEWEX Hydrometerology Panel (GHP), and (3) the GEWEX Modeling and Prediction Panel (GMPP). GRP and GMPP have contributed to an improved understanding of energy fluxes, the cycle of water through the climate system, and of clouds and their radiative interactions. GHP has sponsored continental-scale energy and water cycle experiments (CSEs) that have provided a better understanding of land surface/atmosphere processes leading to improved representation in models of these disparate regions of the globe. CSEs that contribute to regional monsoon studies include the GEWEX Asian Monsoon Experiment (GAME), GEWEX Americas Prediction Project (GAPP) in North America, and the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA). The CSE's have typically concentrated on land-atmosphere interactions and variability on diurnal to intraseasonal time scales. GEWEX employs a wide variety of models, including but not limited to, cloud resolving models (CRMs), and regional climate models (RCMs). As noted above, these models typically have much higher horizontal resolution (10's km) and vertical resolution compared to the GCMs employed in CLIVAR studies. Also, they tend to employ more detailed parameterizations of unresolved physics compared to GCMs.

In section 2 we present a synopsis of the workshop presentations which can be found at: http://www.clivar.org/organization/aamon/WCRPmonsoonWS/agenda.htm (Note: in this section we refer to the presentation(s) from which our synthesis was derived. The respective presentations may contain journal article citations that the reader can refer to for more detailed information). In section 3 the recommendations of the three working groups are highlighted and in section 4 summaries of the individual presentations and the three working groups are given. The appendices contain the workshop program and the listing of the workshop participants.

2. Synthesis of the Workshop

The first session consisted of overviews of key modeling and observational issues from representatives of CLIVAR and GEWEX monsoon panels and projects. In the second session invited presentations were given regarding fundamental physics and dynamics of monsoons. This section of the report gives a synthesis of the presentations with emphasis on common problems that plague the different monsoon domains. The commonality of problems does not imply that their underlying causes (e.g., poorly represented processes) are the same for each of the domains considered. In global GCMs, typically used for seasonal, interannual, decadal, and climate change studies, limiting factors to improved simulation of the Earth's monsoon systems include the inability to adequately resolve the complex orography and the multi-scale interactions that contribute to the seasonal mean monsoon.

a. Orography

Resolving complex terrain provides a challenge to modeling monsoon regions since it has a strong influence on the ability to resolve multi-scale interactions. Additionally, inadequately resolving orography compromises the ability to assess regional impacts including those due to extreme events. For example, the orography of the Asian summer monsoon domain (e.g., the western Ghats, the Burma highlands, the Tibetan Plateau, and The Philippines) acts as anchor points of locations of precipitation maxima. Poorly resolving the orographic anchor points contributes to errors in the amplitude and spatial distributions of rainfall. In GCMs the Asian monsoon rainfall is typically underestimated and too spread out (Wang and Kolli). In RCMs the better representation of orography contributes to a better simulation of the mean monsoon rainfall over Eurasia (Y. Wang). Properly representing the large-scale orography of the Tibetan Plateau is essential for representing the tropical atmospheric and oceanic climate through its influence on the east-west circulation that can alter the evolution of the Asian summer monsoon (Kimura). Adequate resolution of the orography over the Maritime continent is essential for being able to capture diurnal land-sea breeze influences that extend hundreds of kilometers offshore (Slingo). Over South America resolving the Andes Mountains is important as they tend to isolate the Pacific from that of the continent to the east, especially in the lower troposphere. This is important for resolving flow along the west coast of South America where errors in sea surface temperature (SST) occur that can affect warm season rains (Kirtman), but also for capturing the multi-scale interactions over the continent (Saulo and Nogues-Paegle). Numerical experiments also suggest the importance of resolving the orography of Brazil (Silva Dias and Berbery). Resolving the complex terrain of the North America Monsoon region provides a challenge to modeling this region since it has a strong influence on the ability to resolve multi-scale interactions. For example, over Mexico the complex orography of the Sierra Madre Occidental (SMO) is one key toward resolving the warm season rainfall, including variations on diurnal time scales that emanate from the SMO.

b. The Diurnal Cycle

The diurnal cycle of precipitation was noted as being particularly problematic in GCM simulations. The diurnal cycle is a forced mode of variability that needs to be adequately captured in order to properly represent the moisture and heat budgets over both ocean and land. In observations the phase of maximum precipitation often exhibits a systematic phase change from land to ocean or mountain to plain (Kimura, Higgins). In GCMs it is not uncommon for the time of maximum precipitation to peak anywhere from ~2-6 hours out of phase with observations (Slingo, W. Lau, Higgins, and Randall). The evolution of the planetary boundary layer (PBL) is intimately related to the surface diurnal heating that is essential for the organization of cumulus cloud ensembles.

Simulations of a GCM with an embedded 2-dimensional cloud resolving model in place of a typical convection scheme resulted in a much more realistic diurnal cycle of convection. Results suggest that as a minimum coupling between the PBL and deep convection is necessary to improve the diurnal cycle in GCMs (Randall). Based on observations over Amazonia and results from a CRM, realistic representation of the diurnal cycle of rainfall requires turbulent moisture convergence at the top of the PBL. In order to adequately realize this in a GCM it was necessary to increase the vertical resolution in the PBL. Added benefits included an improved representation of the South Atlantic Convergence Zone and a reduction of SST errors over near-coastal stratocumulus regions (Mechoso et al.). The Arakawa-Schubert convection scheme contains a PBL sub-model that tends to give a more realistic representation of the diurnal cycle of precipitation than convection schemes that do not have a similar sub-model (Mechoso et al., Randall).

In coupled ocean-atmosphere GCMs, inadequate vertical resolution of the upper ocean precludes adequately representing the diurnal cycle of SST. In observations over the ocean under light wind conditions a strong diurnal cycle in sea surface temperature tends to be present with cumulus congestus clouds being most prevalent in the late afternoon. Thus, an inadequate representation of the diurnal cycle of SST in models can also lead to an unrealistic radiation balance with poor phasing of the surface fluxes compared to observations. A poor representation of the diurnal cycle of SST may also contribute to a poor representation of intraseasonal oscillations (ISO) since this may preclude adequate moistening of the atmosphere by shallow convection, which is a necessary precursor to the deep convection that occurs during the active phase of the ISO (Waliser).

Errors in the amplitude and phase of the diurnal cycle of precipitation also exist over land (Silva Dias and Berbery, Kirtman, Giannini et al., Lawrence) indicating that a better understanding of land-atmosphere interactions is required. It was found that models with weak land-atmosphere coupling tend to exhibit onset and peak diurnal rainfall earlier than in observations. Possible reasons for weak soil moisture-precipitation feedback in models include the ability of the land surface scheme to partition energy into the latent and sensible heat components, inadequately resolving the boundary layer, including weak mixing from above, and convection schemes being too sensitive to instabilities in the boundary layer (Lawrence). The elevated heat source of the Tibetan Plateau also exhibits a strong diurnal cycle with Regional Climate Models (RCMs) capturing mountain-valley circulations and convection, as well as lee-side diurnally forced squall lines over Indo-China (Kimura).

Low-level jets (LLJs) are an integral component of monsoons that provide the conduit for the transport of moisture that fuels monsoon systems. LLJs exhibit a strong diurnal component that also affects rainfall. LLJs are intimately related to numerous processes including (but not limited to) planetary boundary layer processes, large-scale upper-level synoptic influences, land-sea contrast, surface friction, and land-surface interactions (Saulo and Nogues-Paegle). Modeling studies indicate that land-atmosphere coupling is particularly strong over India, East Asia, West Africa, and the Great Plains of North America (Polcher). The complicated interactions involved in their formation and maintenance provides an excellent testbed for understanding interactions of a multitude of physical parameterizations. Improvement in the simulation of LLJs should lead to a better representation of the phase and amplitude of the diurnal cycle of precipitation and thus the warm season rain. This is a severe test for models given the unique land-sea distributions, surface types, and orographic influences of the disparate monsoon regions.

RCMs are typically superior to GCMs in representing the diurnal cycle of precipitation. With better resolved orography and more comprehensive physical parameterizations important aspects of monsoon are realized, including rapid frontal transitions over China associated with Mei-yu/Baiu front (Y. Wang). Increased horizontal resolution in a GCM also resulted in a better simulation of the afore-mentioned frontal transitions over East Asia (Kimoto). Given the much longer time scales considered in GCM simulations, and in many cases the need for ensembles of integrations, it is not viable to simply transplant the more complex physics directly into a GCM. Rather, through a better understanding of the important physical processes it may be possible to develop more complete parameterizations for GCMs. Of course, detailed observations on which to base the way forward are essential for success.

c. The Tropical Intraseasonal Oscillation

The tropical intraseasonal oscillation (ISO) is a dominant mode of variability that controls convection on time scales of ~30-70 days over the Asian-Australian sector and to a lesser extent over Central and South America and Africa. Here, the general term ISO is meant to encompass the Madden-Julian Oscillation and the boreal summer intraseasonal variability. The ISO influences the ocean by generating equatorial Kelvin waves, and thus they may be a factor in the onset, and amplitude of El Nino events. Given the large spatial scale and persistence of its associated convection the ISO also exhibits teleconnections into the extratropics. The time scale of the ISO bridges the gap between numerical weather prediction and climate simulation, and adequate simulation of the ISO could contribute dramatically to more accurate medium-range and seasonal forecasts. Simulation of the ISO has proven to be a severe test of models. It is typically represented poorly in all classes of models indicating that fundamental understanding and parameterization of the complex interactions that contribute to the life-cycle of ISO's is lacking (Waliser). Typically, simulations of the ISO are too weak, they exhibit less coherence in their propagation and the simulated time scale is too short. During boreal winter the observed propagation is predominantly eastward, and in boreal summer there is also a northward component that together are manifested as a rainband with a pronounced northwest to southeast tilt. In GCMs, if propagation is even present, it is not uncommon for the boreal summer tilt to be reversed compared to observations (Wang and Kumar Kolli). Poor representation of the boreal summer ISO is linked to poor boreal winter ISO simulation (Wang and Kumar Kolli, Waliser). The fidelity of the eastward propagation is demonstrated to be sensitive to the critical threshold required before convection is initiated (Kimoto).

Air-sea interaction and a realistic basic state are important for properly representing ISOs. That air-sea interaction is important for organizing the convection (also see the diurnal discussion above for the potential role of air-sea interaction for pre-conditioning the atmosphere during the quiescent phase of the ISO) suggests that monsoon simulations require an interactive ocean, especially for the Asian-Australian monsoon. However, in some instances an uncoupled integration can better simulate an ISO than the atmospheric model run with prescribed SSTs. This is usually due to shortcomings in the air-sea coupling that can compromise the simulation of ISOs in coupled models (Duvel). Sensitivity studies suggest that 1m vertical resolution and hourly air-sea coupling may be necessary to resolve the diurnal variations that rectify back on to the ISO (Woolnough et al.). Mean state errors in GCMs, such as the inability to simulate the low-level wind climatology over the Indian Ocean and west Pacific (Woolnough et al.) and a "split-Intertropical Convergence Zone" in the central/west Pacific are limiting factors in our ability to simulate the ISO.

Perfect predictability studies with climate models suggest that skill in predicting the ISO may extend out to 25 days, though present dynamical predictions fail to exceed the 15-25 days skill of statistical and empirical methods (Waliser). The importance of intraseasonal prediction is paramount, and cannot wait for better dynamical models to be developed. As such, a system for forecasting the "slow-manifold" using wavelets has been successful for regional boreal summer monsoon forecasts of Ganges-Brahmaputra river discharge. The ramifications of improved predictability include improved land use, choice of crop and sowing time, drought and flood mitigation etc. (Webster et al.).

d. The Seasonal Cycle

The seasonal evolution of the monsoon is also a challenge for GCMs. Most GCMs exhibit too early an onset of the Asian monsoon (Wang and Kumar Kolli) though in some cases too weak of a Somali Jet is associated with late onset of Indian monsoon rainfall (Lord et al.). Even though the mean and seasonality of SST and the tropical circulation have improved in a model with revised convection, PBL, clouds and land surface model, improvement of the Indian monsoon is lacking (LeTreut). Over the North American monsoon region the simulated onset is delayed by one month compared to observations. Results indicate that the seasonal cycle of North American monsoon rainfall is better simulated at a horizontal resolution of T126 than T62 (Higgins). Over South America the seasonal cycle of monsoon rains tend to be better represented than other monsoon regions of the Earth (Kirtman).

Ensembles of hindcasts of boreal summer over North America indicate that the location of the monsoon anticyclone is sensitive to the initialized soil moisture (Higgins).

Hindcasts of seasonal to interannual time scales using ensembles of GCM simulations indicate that the multi-model ensemble skill exceeds that of any individual model. However shortcomings remain due to parameter uncertainty. Sensitivity tests with a numerical weather prediction model that includes a cellular automaton stochastic backscatter scheme produce a realistic k-5/3 energy spectrum not captured in the standard model configuration, and yields a better simulation of seasonal mean rainfall (Palmer).

e. Interannual Variability

The teleconnection between ENSO and the Asian summer monsoon is well established in observations. Skill in forecasting NINO3.4 SST now exceeds canonical correlation analysis, constructed analogue and other statistical measures (Lord et al.). GCM modeling studies indicate that during El Nino the below-normal heating over Indonesia and the western Pacific contributes to the development of a low-level anticyclone that tends to lead to below-normal monsoon rainfall. Air-sea feedback imparts a biennial tendency in monsoon rainfall interannual variability. In the model, El Nino enhances the intraseasonal variability over the western Pacific (G. Lau). Other GCM studies find that interannual variations of the Asian summer monsoon are poorly represented due to their failure to properly project the subseasonal modes onto the seasonal mean anomaly. In the absence of air-sea interaction the Asian summer monsoon teleconnection with ENSO is not properly realized. This, in conjunction with the afore-mentioned need for air-sea interaction for capturing ISO activity, suggests that prescribed SST experiments and two-tiered forecasts may not be adequate for simulation and prediction of monsoon rainfall. Additionally, the fidelity of the interannual variability is linked to the quality of the mean state (Wang and Kumar Kolli).

f. Observations

Observations are key for understanding processes in the climate system, obtaining real-time data for assimilation into numerical weather (and seasonal to interannual) prediction models, boundary conditions for regional and cloud resolving models, parameterization development to simulate unresolved scales, and for model validation. A detailed analysis of the present observing system and observationally based datasets (e.g., reanalysis) was not possible given the time-limitations of the workshop. Great concern was voiced over the decay of the observing system, in particular the decrease in the number of sites from which routine sondes are launched. It was stressed that in situ data are needed despite the revolution in satellite data acquisition that is presently underway. The new satellite products will enable near global observations of the water and energy cycle on diurnal and longer time scales (W. Lau, Waliser). Newly acquired satellite data have revealed shortcomings in the representation of the vertical profile of moisture in reanalysis during the life cycle of the MJO (Waliser).

The WCRP/GEWEX Coordinated Enhanced Observing Period (CEOP) program is an example of the approach of multiscale evaluation in terms of time scale and models. Global to station observations obtained from 2001-2004 will allow the validation of a hierarchy of models (W. Lau). New concerns were voiced regarding the role of high levels of aerosols over the Asian/African region, and their role in the water and energy cycle. In addition to acting as cloud condensation nuclei (and therefore as heat sources and sinks in the atmosphere), aerosols also perturb the radiation balance.

The extent to which these effects feedback to influence the monsoon mean state and variability is an open question.

Over Africa the current sustained observing system is not adequate to (1) evaluate and improve models of key phenomena and processes (e.g., diurnal cycle, heat low, African Easterly Jet, etc.), (2) support climate prediction and its impact, and (3) for validating satellite products. To begin to address these shortcomings the African Monsoon Multidisciplinary Analyses (AMMA) project is a comprehensive observational campaign of the West Africa Monsoon that will take place in 2006 (Polcher). In addition to a better understanding and prediction of the physical system, including atmospheric, oceanic, biological, and chemical (aerosols), a major goal is to address socio-economic impacts due to environmental change, land use, and human activities. The results from AMMA should also help establish the configuration of a sustained observing system over Africa.

Enhanced observations gathered during the North American Monsoon Experiment (NAME) 2004 provide an unprecedented set of atmospheric, ocean, and land surface data for investigating the relationship between moisture transport and monsoon onset and surge events, and understanding the diurnal cycle of moisture over the ocean and complex terrain. The diurnal signal in rainfall initiates over the Sierra Madre Occidental and then propagates to the east and west where the strongest rainfall signal occurs. Future NAME milestones include the assessment of global and regional model simulations of NAME2004, the reproduction of the diurnal cycle of observed precipitation over the core monsoon region, evaluation of changed parameterizations, quantification of the relative roles of ocean vs. land surface influences, and improvement of the skill of warm season rainfall forecasts (Higgins).

The South American Low-Level Jet Experiment (SALLJEX) was carried out in November 2002-February 2003. Goals included an improved representation of the tropospheric flow on diurnal and longer time scales due to the heretofore sparse sounding network, and a better understanding of the vertical structure of the LLJ along the Andes and its relationship with mesoscale cloud systems and precipitation. Hindcasts using SALLJEX in their initialization data showed an improved representation of regional rainfall anomalies in 24 hour forecasts (Kirtman).

While there was no formal presentation on the Indian Ocean observing system of buoys, in plenary the attendees acknowledged the importance of this developing resource for understanding air-sea interaction and the role the Indian Ocean plays in the summer and winter monsoon. The lack of routine Indian Ocean observations is seen as an impediment to progress in understanding key processes and forecasting of the Asian monsoon. Implementation of GOOS/CLIVAR Indian Ocean Panel plans for an enhanced and sustained ocean observing system in the region is seen as a priority. The VASCO/CIRENE activity is a series of observational campaigns in the western Indian Ocean just south of the equator in which ocean-atmosphere observations have been/will be taken in boreal winters of 2005-2007. Measurements include those associated with ocean physics, air-sea fluxes, the atmosphere, and ocean biogeochemistry. The experiment will revolutionize our understanding of processes related to: (1) the role of the diurnal cycle in warm layer formation in the upper ocean, (2) the origin of intraseasonal SST variability, and (3) seasonal to interannual variations of equatorial wave dynamics and ocean mixed layer physics (Duvel).

In early 2006 the Tropical Warm Pool International Cloud Experiment will take place with the focal point being Darwin, Australia. From surrounding land and ocean locations radiosondes, precipitation and cloud radars, flux sites, aircraft, and satellite measurements will be taken. This will be the first time that coordinated measurements of cloud properties and their effect on the local environment will be taken in combination with measurements of the heat, moisture, and momentum budgets. The emphasis will be on cirrus clouds since they are not well understood. The new data will also be a resource for validating CRMs and parameterization development for global models (Jakob).

New approaches of investigating systematic model error include the US Department of Energy Climate Change Prediction Program Atmospheric Radiation Measurement Parameterization Testbed (CAPT) in which station observations are used to investigate error growth in GCM hindcasts that have been initialized from reanalysis. The CAPT testbed has proven to be a valuable tool for investigating sensitivities to different parameterizations (Potter). Interest in expanding the CAPT approach to additional models and for the CEOP (and other) station data was expressed (W. Lau, Waliser, and Jakob).

3. Working Group Recommendations

Through the working group and plenary discussions consensus was that more effort and collaboration is needed for improving monsoon modeling and prediction. In the near-term the emphasis should be on improving the diurnal cycle of precipitation in global models. Over both land and ocean global models typically exhibit large phase errors compared to observational estimates. Given that regional and cloud-resolving models perform much better in this respect, we envision that a better understanding of the factors involved (e.g., physics and resolution) in realistically simulating the diurnal cycle in these models can be translated to an improved representation in global models. This will promote closer interaction in monsoon-related modeling activities under CLIVAR and GEWEX as part of a new Pan-WCRP initiative of monsoon research within the COPES activity. The regional climate modeling studies and numerous (GEWEX Cloud System Study) (GCSS) working group efforts provide fertile ground for initiating collaboration with CLIVAR for improving the diurnal cycle of convection in GCMs. Input from experts in land-atmosphere interactions (e.g., Global Land Atmosphere Coupling Experiment [GLACE]) also will be an essential component to this task, and CAPT experiments may help address issues regarding error growth and parameterization sensitivity. As noted previously, improving the diurnal cycle of precipitation and clouds may improve the representation of the ISO. Irrespective of this potential, we also recommend enhanced interaction between CLIVAR and GEWEX in the study and modeling of the ISO phenomenon itself. Both of these tasks involve a better understanding of numerous processes. A comprehensive list of recommendations is given below in terms of Science Recommendations, Barriers to Progress, and Implementation Mechanisms.

a. Science Recommendations

- Improve the simulation of the diurnal cycle of precipitation and convection in global models. This will be achieved by making use of regional climate models and cloud-resolving models that have more comprehensive physics. This is the primary near-term goal that will crosscut the expertise of CLIVAR and GEWEX.
- Improved modeling of intraseasonal oscillations, which affect large-scale convection in the tropics on a time scale of ~30-70 days. Closer cooperation between CLIVAR, GEWEX, and CAPT activities may lead to a better understanding and improved modeling of the ISO (irrespective of the possible improvement in ISO that may arise to better simulation of the diurnal cycle of clouds and convection).
- Improved modeling of surface fluxes, the planetary boundary layer, and clouds.
- Perform more process studies and modeling of the Maritime continent and the Indian Ocean.
- Achieve a better understanding of the atmospheric moisture distribution and transport.
- Improved representation of the planetary boundary layer, including an integrated approach to evaluating physics parameterizations and their interactions.
- Sensitivity testing to determine the resolution necessary in global models to simulate multi-scale interactions that dominate the Earth's monsoon systems.
- In regional climate models (RCMs) a better understanding is needed of the limitations imposed by having to specify lateral boundary conditions. Alternative nesting techniques, such as two-way nesting, need to be explored. This may help in understanding scale interactions across the different resolved spatial scales.

- Achieve greater fidelity in the simulation of the equatorial cold tongue in the Pacific Ocean, the sea surface temperature in the tropical Atlantic Ocean, and the western boundary currents.
- Improved (and sustained) observations are needed over sparsely sampled regions of the tropical oceans, especially the Indian Ocean.
- The role of land-atmosphere coupling needs to be benchmarked against observations.
- Better observations of land surface conditions are needed (e.g., soil moisture, snow cover, snow depth) for understanding processes, and because these quantities can serve as boundary conditions for model simulations.
- The role of aerosol and dust and its impact on the development of monsoon precipitation should be investigated, though at present these may be secondary to errors in the basic structure of monsoon simulations.
- The importance of air-sea interaction for modulating intraseasonal variability and for capturing the monsoon-ENSO teleconnection suggests that use of coupled ocean-atmosphere models is a key requirement for monsoon prediction.

b. Barriers to Progress

- The decay of the observational network needs to be reversed, with the network expanded into regions where observations are scant.
- Raise the profile of model and parameterization development. This calls for a sustained funding commitment from agencies.
- Lack of adequate computer facilities for the sensitivity testing to understand complex processes and their feedbacks. Testing the spatial resolution and temporal resolution and physics dependencies should be considered a "Grand Challenge" problem to the modeling community in terms of scientific effort and computing.

c. Implementation Mechanisms

- Establish a Pan-WCRP monsoon panel/working group within the COPES initiative.
- Hold targeted workshops to foster interaction for sustaining CLIVAR and GEWEX interactions. These can be held in conjunction with existing panel meetings, as sessions at conferences, or independently. The first will be focused on the diurnal cycle over ocean and land.
- Continue the process, started at the workshop, of building of an agreed list of priorities that could be facilitated by Pan-WCRP interactions.
- Develop a joint CLIVAR-GEWEX approach to the Asian-Australian monsoon, building on the current CLIVAR-GEWEX collaboration on the American and African monsoon systems.

4. Summaries of the Presentations

a. An Overview of Key Modeling Issues and Observational Requirements

CLIVAR Asian-Australian Monsoon Panel
B. Wang and R. Kumar Kolli

The CLIVAR AAMP panel has actively been engaged in numerical modeling of the Asian-Australian monsoon system. Identification of errors in uncoupled (sea-surface temperature prescribed as the lower boundary condition) and coupled general circulation models (GCM's) have been pursued to identify common model errors and to set the priority for future field studies.

Systematic model evaluation of Asian-Australian monsoon variability has been performed for uncoupled atmospheric GCM's. Three key simulation aspects include (1) the mean seasonal cycle of rainfall, (2) the tropical intraseasonal oscillation, and (3) interannual variability. With regard to item 1, the boreal summer rainfall is particularly problematic over the western Pacific, where models typically underestimate that observed, and they fail to represent the Mei-Yu rainband. Over the Indian sector the rainfall is better simulated, relatively, but substantial errors still exist in amplitude and location. For example, the location of rainfall maxima adjacent to the western Ghats and over the Bay of Bengal are more spread out than observed, and many models fail to represent the near equatorial rainfall maxima over the Indian Ocean. In terms of the seasonal evolution, over the Indian and Western North Pacific (WNP) sectors the summer monsoon onset occurs too early in the models. Over India the rainfall is too strong while over the WNP region the models bifurcate into two groups (above and below observations).

A second key feature of the monsoon is the tropical intraseasonal oscillation, which dominates subseasonal variability on time scales of ~30-70 days. The intraseasonal variability is the dominant influence that controls the active and break phases of the monsoon. During boreal winter the intraseasonal variability is dominated by eastward propagation while in summer there is also a northward propagation component. Simulated intraseasonal variability tends to be too weak and not as coherent as observed. A poor representation of boreal summer intraseasonal variability is strongly linked with poor winter intraseasonal variability. During the summer the models tend to produce a southwest to northeast tilted rainband, rather than the observed northwest to southeast tilt. The relationship between the intraseasonal convection and the surface fluxes is incorrect when SST is prescribed. Air-sea interaction is important for properly representing the intraseasonal variability, but the SST climatology (in addition to other variables) in a coupled ocean-atmosphere GCM must also be well represented, otherwise the convective centers will be incorrectly located.

Interannual variations of the summer monsoon are poorly represented in AGCMs forced with observed SST. Dynamical features are better represented than the rainfall, and the fidelity of the interannual variability is directly related to the quality of the mean state. The models fail to properly project the subseasonal modes onto the seasonal mean anomalies, compromising the interannual signal. AGCMs also poorly represent the ENSO-monsoon rainfall teleconnection due to the lack of air-sea interaction. This suggests that AMIP-type experiments and two-tiered forecasts may be inadequate for the simulation and prediction of monsoon rainfall.

GEWEX Asian Monsoon Experiment Modeling Activity
F. Kimura

The GEWEX Asian Monsoon Experiment (GAME) modeling has focused on understanding major Asian monsoon processes as follows: (1) Continent-Ocean Thermal Contrast, (2) Elevated Heat Source (Tibet Plateau), (3) Sub-tropical Jet (or Westerly), (4) Tropical heat source, and (5) Diurnal cycle. One important phenomenon related to (1), (2) and (3) is the dynamics of the Meiyu/Baiu front (MBF) in the east Asian monsoon system. RCM studies revealed the coupling process of subtropical jet stream (STJ) and low level jet (LLJ) in the lee side of Tibetan Plateau (TP). Basically, the MBF is formed by the deformation of the zonal mean field due to the land-sea contrast and TP topography, though the location of the MBF is quite sensitive to the zonal mean field. Moisture transport and condensation processes are also important for a realistic LLJ. Moisture transport to the MBF from the wet land surface (e.g., water-fed paddy field) contributes to enhancement of convective systems embedded in the MBF. The location of STJ relative to TP has also been revealed to be crucial for the formation of desert climate to the west and/or north. A series of coupled ocean-atmosphere GCM experiments with different mean altitude of TP suggested that the TP with the current altitude (~ 4000-5000m) is essential for the formation of the warm water pool in the western Pacific through the intensification of east-west atmospheric circulation and its coupling to the ocean state.

The diurnal cycle of precipitation and convection is a prominent feature of the Asian monsoon system, especially over the TP. RCM experiments proved that the mountain-valley undulation with an amplitude (altitude difference) of 1-2km, and wave length of about 100-300 km over the TP has proved to be very effective for producing the diurnal cycle of mountain-valley circulations associated with convection and precipitation. Over the Indo-China Peninsula the diurnal cycle of convective clouds are activated in the evening at the lee-side foot of the Dawna-Tennasserim mountain ranges located at the west and middle of Thailand and then are organized into squall lines that travel eastward during the night at about 5-10 ms^{-1}. These squall lines weaken around midnight. A cloud-resolving model (CRM) experiment well simulated the propagating diurnal cycle systems, and also revealed that the solar-synchronized life cycle of the squall lines and their eastward movement cause the nighttime maximum of the precipitation over the inland area of the Indo-China Peninsula.

The Asian monsoon region is a heavily-populated area and the impact of land use/change should be a serious issue to be assessed under the monsoon climate. A RCM experiment suggested that deforestation of the Indo-China peninsula in recent several decades may be responsible for the remarkable decreasing trend of observed rainfall in September when monsoon westerlies are seasonally weakened. The selective response of rainfall anomalies to land cover/use change may be an important characteristic in land-atmosphere interaction in the monsoon climate. A similar but re-greening impact of desert to grassland in the Gobi-desert area was also investigated using another RCM. This experiment shows that the increase in rainfall largely occurs due to an increase in intensity rather than an increase in frequency. Lack of frequent rainfall, especially in the lowlands of the test area, makes it very difficult to maintain a vegetated surface. This implies that the current vegetation restoration activities will be largely limited to areas where water resources are relatively abundant, or they will depend heavily on irrigation. Changes in regional circulation also induce some remote responses to other areas of China.

VAMOS Modeling
B. Kirtman

VAMOS can provide unique contributions to model development in the areas of land surface processes through its North American Monsoon Experiment (NAME) and Monsoon Experiment South America (MESA) and of boundary layer clouds through the VAMOS Ocean-Atmosphere-Land Study (VOCALS). VAMOS can also provide important contributions to improvement of model performance in the areas of 1) representation of orography, 2) cloud-radiation interactions, 3) diurnal cycle, particularly for convection over land, and 4) atmosphere-ocean interactions. VAMOS will also use models for hypothesis testing and assessing the impact on predictability of data collected in process studies.

The main issues of VAMOS modeling include poor simulations of warm season climate, precipitation, and diurnal cycles. The main science themes to be addressed are (1) SST variability in the Pan-American seas, (2) monsoon maturation, onset and demise, (3) improving the prediction of droughts and floods, and 4) diurnal cycle of precipitation and clouds.

The elimination of warm SST biases off the Peruvian coast and east Pacific in CGCMs is crucial for better simulation of warm season climate. VOCALS aim to improve SST prediction, including representation of atmospheric boundary layer (ABL), clouds and ocean mixing in the eastern Pacific. Also, rainfall variability over land may remotely influence surrounding seas (e.g., through coastal winds in the East Pacific).

Seasonal cycle monsoon indices (e.g., rainfall) over South America, including subseasonal events over the continents in summer, were well simulated compared to other monsoon systems in GCMs run with prescribed SST (Marengo et al. 2003).

Assessment of the model representation of extreme precipitation events (spatial extent and duration of extreme events) and related circulations, and model sensitivities to local and remote forcings (e.g., land-surface processes, SST forcings) are being undertaken, which may need further effort as part of Pan-WCRP simulations/predictions (COPES, SMIP, DEMETER, ENSEMBLES, CTB, APCC ...). Parameterization and resolution sensitivity (i.e., convection, clouds ...) studies may also be essential.

The model representation of the diurnal cycle in the South American Monsoon System (SAMS), North American Monsoon System (NAMS) and South Equatorial Pacific (SEP) regions is still challenging. Most of models have not been successful in simulating the diurnal cycle of rainfall (e.g., late maximum and amplitudes). Local vs. remote processes (e.g., soil moisture, moisture supply by LLJs, role of land-sea breeze) need to be examined further. In addition, rectification of the diurnal cycle on to (sub-) seasonal time scales, and role of the diurnal cycle in extreme events need to be studied.

MESA: Modeling Issues in the Main River Basins of the South American Region
P. Silva Dias and H. Berbery

The structure of the South American monsoon: onset, withdrawal, intraseasonal variability, interannual and decadal variability was described. The South Atlantic Convergence Zone (SACZ) is a major feature in MESA. Model challenges are summarized as follows:

1) In the Amazon basin models do not reproduce some important characteristics of the observed rainfall (e.g., they have an excess rain in the SACZ and low precipitation in the Amazon). Models also do not reproduce the observed phase and amplitude of the diurnal variation of convection. Poor representation of diurnal cycle of convection (and heat source) in the tropical sector of South America may affect teleconnections (e.g., through Kelvin waves in generating the basic state favorable for cross equatorial energy transfer in the equatorial Atlantic).

2) Low predictability of the SACZ on the seasonal time scale (including control of the SACZ location and intensity by local versus remote effects).

3) Potential interaction with biomass burning aerosols in the onset, as suggested in examples in a Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) experiment.

4) Hydrological modeling (e.g., the Pantanal challenge).

Diagnostic studies based on global data sets have revealed that: 1) ENSO produces large, reasonably reproducible spatial and temporal shifts in precipitation over tropical and subtropical South America during spring and summer. 2) The Antarctic Oscillation (AAO) has a significant contribution in spring while the Pacific South American (PSA2) pattern has it in summer and fall. These results indicate that a significant portion of the skill of climate forecast models will likely arise from an ability to forecast the temporal and spatial variability of ENSO and the associated teleconnection patterns into mid-latitudes as well as the variability associated with the AAO and the PSA2.

Other possible causes of poorly simulated low precipitation in the Amazon and excessive rain in the SACZ may be related to interaction with the biosphere. For example, SIB (simple biosphere model) and other models behave quite well when forced with observed data but runaway in coupled form. Diagnostics also suggested problems with treatment of soil moisture.

Understanding the positive feedback loop in precipitation and ecosystem stress and the role of the Amazon are critical questions. Some recent studies have tried to answer these questions finding that:

1) The results indicate a significant role of the soil moisture in setting up temperature anomalies and circulation anomalies that might explain the intraseasonal changes reported by Grimm (2003, 2004).
2) Atlantic SST anomalies off the southeast coast of Brazil also seem to exert an influence on regional rainfall.
3) An interesting effect of the orography in central-east Brazil on the monsoon circulation and precipitation is disclosed by experiments with flat terrain in this region. This is a new aspect, since up to now the studies on the influence of orography on the South American climate have been focused on the role of the Andes Mountains.
4) The precipitation-soil moisture interactions over the SAM reveal a positive feedback at time scales longer than ~2 weeks.
5) Soil over the SAM region seems to be close to saturation, and therefore increases of soil moisture have less impact on precipitation than decreases of soil moisture.
6) Variations in photosynthesis and respiration in tropical forests are strongly influenced by soil moisture.
7) Variations in evapotranspiration due to ecosystem drought stress may interact with regional precipitation and climate.
8) Ecosystem response to seasonal and interannual drought can help us to test the ability of models to represent physiological stress in tropical forests.

Low predictability of the SACZ is closely related to small changes in intensity and location of the SPCZ which may change the sign of the anomalous circulation in the SACZ region. Local effects of soil moisture are also important (Grimm et al., Berbery et al.).

The LBA experiment mentioned above also strongly suggests that potential interaction may exist between the onset of monsoon over Amazonia and biomass burning of aerosols through the influence of diffuse radiation in cloud dynamics as seen during the transition from the dry to the wet season in Rondonia. Further study may be needed to understand this interaction (e.g., role of biogenic cloud condensation nuclei after continuous rains, recycling of aerosols through rainfall and role of aerosols in surface and PBL energy budgets).

Through MESA experiments and modeling, some general conclusions are obtained as follows: (1) climate and climate change over land depends largely on correctly representing evaporation/precipitation feedbacks, and therefore to understand the controls on evapotranspiration is critical. In areas away from the monsoon, and monsoons in transition phases (between dry and wet seasons), precipitation largely depends on evapotranspiration (and the soil moisture condition), (2) there is a tight control between the surface energy budget and sub-cloud layer structure and therefore with cloud-base and cloud cover (critical elements in the climate response). At the surface the impact of the vegetation state (greening, flowering, etc.) on the surface energy budget is significant, and (3) significant differences are found between these relations in models and observations (e.g., higher cloud bases in models than observations; enhanced sensible heat dependency on cloud base in models; larger sensible heat in models than observations under same cloud base conditions: larger dependency of observed evapotranspiration on cloud base than models).

Variability of African Climate System (VACS)
A .Giannini, C. Thorncroft, and K .Cook

An overview of VACS was presented at various time scales, including the diurnal cycle, intraseasonal oscillation, seasonal cycle, and interannual variability. The key features of the mean West African monsoon system (WAM) are the heat low and dry Saharan Air Layer (SAL) over the Sahara desert, moist monsoon flow and the ITCZ to the south of the SAL, the African Easterly Jet (AEJ) between the SAL and monsoon air, and the cold tongue of the Gulf of Guinea. In synoptic and the mesoscale, African Easterly Waves (AEWs) along the AEJ, tropical cyclones (TC) over the Gulf of Guinea and mesoscale cloud systems (MCS) embedded in AEWs are key features. The AEJ is important for dust and aerosol transport to the Atlantic region. The diurnal cycle is dominated in heat low and associated circulations, and the southerly monsoon flow is active at night and in the morning.

Some key modelling and observational issues have been raised in VACS. For example, the monthly mean AEJ and diurnal cycles are not well simulated in the state-of-the-art GCMs. Scale interactions in time and space (e.g., AEJ, AEWs and TC, MCS) may be important for maintenance of the large-scale circulation. For the interannual and decadal time-scales a SST-prescribed GCM experiment strongly suggests that both remote and local oceanic forcing are important for Sahel and coastal monsoon rainfall in west Africa, though land-atmosphere interaction is likely to amplify the anomalies. The simulation of the West African monsoon system using coupled ocean-atmosphere GCMs is still challenging both in the mean state, and predictions related to global warming scenarios.

The current sustained observing system for the WAM lacks needed observations of the atmosphere, land and ocean and is inadequate to observe the key phenomena and processes needed to evaluate and improve models, and is insufficient to support climate prediction and its impacts. Additionally, operational observing systems in Africa have been decaying in the recent decades. Satellites will likely play a strong role in the future sustained observing system for atmospheric and surface (land and ocean) conditions, but we currently lack appropriate observations to evaluate satellite products. The AMMA research and field campaign offers us a unique opportunity to solve these issues.

African Monsoon Multidisciplinary Analyses (AMMA)
J. Polcher

Significant reductions in precipitation occurred in West Africa during the 20th century which has had a profound impact on African societies. In particular, western Africa is a hot-spot for the dependence of socio-economical well-being on environmental conditions. Under this background AMMA has been proposed. The aims of AMMA are: (1) to improve our understanding of the West African Monsoon and its physical, chemical and biological environment, (2) to provide the underpinning science that relates climate variability to issues of health, water resources and food security and defining the relevant monitoring strategies, and (3) to ensure that multidisciplinary research is efficiently integrated with prediction and decision making activities.

The work-plan (WP) is geared towards multidisciplinary research between geophysics and the human dimension. In the geophysical sphere, four integrative science and four process studies are planned. Process studies are only the first step towards a better understanding and prediction of the African monsoon. The human dimension focuses on four impact studies: land productivity (WP3.1), water resources (WP3.3), health impacts (WP3.4), and human processes and food security (WP3.2). The socio/economic consequences of environmental changes, land use and human activities are the aim, and evaluations of potential early warning systems and adaptation strategies will be a key outcome. Integrating basic research and applications include: (1) tools and methods, (2) demonstration, and (3) capacity building. Only the integration of the basic research in the activities of the African agencies will ensure a long lasting impact.

How will AMMA contribute to improved forecasts of monsoons? The observing systems put into place in 2006 will allow process studies and improve our understating and the process models developed in GCSS, the Global Land/Atmosphere Study (GLASS), and the GEWEX Atmospheric Boundary Layer Study (GABLS). The modeling WP will integrate this knowledge in the forecasting tools. An African Land Data Assimilation system will be built. The integrative science WPs will validate the interactions of the processes and with the large-scale circulation. The environmental monitoring WP will provide the radio-soundings and surface observations for forecasts. At the end of the project the improvements in forecasts will be demonstrated. The forecasting work will be performed in collaboration with The Observing System Research and Predictability Experiment (THORPEX). The European Union has become one of the largest financial contributors to AMMA, which will integrate the research of various fields of environmental sciences.

Coordination of NAME -Modeling and Field Activities
W. Higgins

The objectives of NAME are the better understanding and simulation of warm season convective processes in complex terrain (TIER I), intraseasonal variability of the monsoon (TIER II), response to oceanic and continental boundary conditions (TIER III), and monsoon evolution and variability (TIER I, II, III). One of the unique features of the NAME program is the collaboration between the observational and modeling communities. A driving hypothesis of NAME is that we must develop proper simulations of relatively small (spatial and temporal) scale climatic variability, especially the diurnal cycle, in the core monsoon region of northwestern Mexico. The science questions of NAME2004 were: (1) How are low-level circulations along the Gulf of California/west slopes of the Sierra Madre Occidental (SMO) related to the diurnal cycle of moisture and convection? (low-level circulation), (2) What is the relationship between moisture transport and rainfall variability (e.g., forcing of surge events; onset of monsoon details)? (moisture transport and budget) and (3) What is the typical life cycle of diurnal convective rainfall? and (4) where along the western slope of the SMO is convective development preferred? (diurnal cycle).

The NAME Model Assessment Project (NAMAP) results include: (1) seasonal rainfall maximum in the global models delayed one month. (2) diurnal cycle is not well simulated (including afternoon maximum and nocturnal rainfall), (3) surface fluxes and temperature are poorly constrained, (4) rainfall in T126 simulated better than in T62, and (5) ensembles of warm month simulations (May-Oct 1979-2000) show the location of the monsoon upper-level anticyclone is sensitive to initialized soil moisture.

Related to NAMAP, a mission called “NOAA Climate Test Bed” was also introduced, which accelerates the transition of research/development community and climate community into improved NOAA operational climate forecasts, products, and applications.

CEOP Inter-Monsoon Studies (CIMS)
W.-K. M. Lau

Objectives of CIMS include the better understanding of fundamental physical processes (diurnal cycle, annual cycle, intraseasonal oscillations) in monsoon regions around the world, and demonstration of the synergy and utility of Coordinated Enhanced Observing Period (CEOP) data in providing a pathway for model physics evaluation and improvement. CIMS phase-II (CIMS-II) is now being planned, and its science thrusts are to: (1) continue diurnal, intraseasonal, and seasonal inter-model, inter-monsoon evaluation, and physics improvement with CEOP-1 (EOP3, EOP4) data, (2) extreme event simulation and evaluation; major floods, droughts, El Nino, ISO etc. during CEOP-I (2001-2004) and CEOP-II (out to 2010), (3) aerosol-monsoon water cycle interaction, and (4) coordination with COPES, CLIVAR, IGBP, IGWCO..., pending the outcome of the Pan-WCRP monsoon workshop recommendations.

Models show 2-3 hours early maxima in the diurnal cycle both over land and ocean compared to observations (in-situ and TRMM satellites). This systematic error in simulating the diurnal cycle in models is one of the essential challenges in modeling of monsoon and tropical climate.

The Regional Atmospheric Inter-Model Evaluation Project (RAIMEP) (Coordinator: Y. Wang, IPRC, Hawaii) is being initiated as part of CIMS. The tasks of this project include: (1) to use RCMs as a tool for evaluating physics in global climate models, (2) to examine the performance of current RCMs in simulating the diurnal cycle of the hydrological cycle (clouds, precipitation, surface fluxes, soil moisture...), (3) to identify the common discrepancies and key factors that cause model bias and find pathways to improve model physics, and (4) to use RCMs to provide boundary conditions to drive a CSM in a smaller embedded domain of active convection. Currently, 12 RCMs and one CSM are planning to participate, and the initial focus is on (but not limited to) the East Asian monsoon region in the boreal summer season.

A new aspect of Asian monsoon study as part of CIMS may be aerosol-monsoon water cycle interactions. Suspended particles (aerosol, clouds, and precipitation droplets) in the atmosphere generate diabatic heat sources and sinks through condensation, shortwave radiation absorption, and longwave radiative cooling. Aerosols in monsoon regions are increasing at an alarming rate, with regional and global impacts. A GCM result shows that aerosols warm the atmosphere over land and cool the atmosphere over oceans. Anomalies of vertical temperature (80^{o}-100^{o}E) strongly suggest the "Elevated Heat Pump" effect of absorbing aerosols.

The proposed CIMS implementation plan for Aerosol-monsoon water cycle interactions, include (1) augmentation of the existing CEOP reference sites with measurement platforms to obtain aerosol characteristics over two target regions (Himalaya/Tibet/Northern India, and West Africa/Caribbean), (2) to add current aerosol measurement platforms of AERONET, MPL-NET, ABC, AMMA and others to the CEOP database, and (3) a new initiative entitled Rajo-Megha (dust cloud) (i.e., Radiation, Aerosol Joint Monsoon Experiment over the Gangetic-Himalayas Area), which aims to determine the role of absorbing aerosols in relation to SST, land surface forcing in affecting water cycle dynamics, and predictability of the Asian summer monsoon.

b. Invited Presentations: Fundamental Physics and Dynamics of Monsoons

Modeling and Forecasting Issues Associated with Intraseasonal Monsoon Variations
D. Waliser
Monsoon prediction has been dominated by seasonal to interannual forecasting, though success has been limited. In comparison to boreal winter, when eastward propagation of intraseasonal variability dominates, the summer intraseasonal variability is more complex. It exhibits northward propagation from the equatorial Indian Ocean to the continental latitudes and northwestward propagation over the western Pacific, which are associated with the Rossby wave response to near-equatorial convection. After the onset phase of the summer monsoon (May-June) intraseasonal variance shifts from the Arabian Sea and the Bay of Bengal to the western Pacific (July-October). Locally, the intraseasonal variability modulates the occurrence of monsoon depressions, and in the tropics in general it can affect the occurrence of typhoons and hurricanes. Intraseasonal variability also affects weather in the mid-latitudes, and in the ocean it generates Kelvin waves on the equator that may influence the development of El Nino/La Nina.

The simulation of intraseasonal variability remains a key challenge to climate modelers. The majority of models have intraseasonal variance that is too low, with errors in the spatial distribution and propagation characteristics. The intraseasonal performance in winter and summer is directly correlated. Errors in the mean state of the models (zonal wind, split ITCZ in the west Pacific, etc.) directly impact the verisimilitude of the observed intraseasonal variance. Dynamical forecasts have shown some improvement, though they have yet to meet or exceed the 15-25 day skill of statistical or empirical methods suggest may be possible. Perfect predictability studies with climate models that simulate intraseasonal variability with some fidelity indicate that skill may be extendable to 25 days. It was suggested that assimilation of the statistical/empirical forecasts into dynamical forecasts may be a useful way forward until such time that the dynamical models better represent intraseasonal variability.

Air-sea feedback is an important component of intraseasonal variability that is responsible for the lead-lag relationship between convection and SST. To the east (west) of the convection the SST anomalies are above (below) normal. If intraseasonal SSTs are prescribed to an atmospheric model, the convection tends to lock on to the warm SST anomalies resulting in phase errors of about 7 days

(~2000km) in the tropical heating. Thus, on subseasonal time scales coupling between the ocean and atmosphere is essential, indicating that the two-tiered approach to forecasting is inadequate for the subseasonal problem. Other important aspects for simulating intraseasonal variability include (1) the representation of easterly shear during boreal summer for the development of northward propagation, (2) adequate vertical resolution to represent the cumulus congestus phase of convection that contributes to destabilization of the atmosphere in advance of the deep convection, and (3) radiative heating feedback that amplifies the latent heating.

A full understanding of the essential processes for simulating intraseasonal variability is lacking. This is reflected by the ability and/or inability of successive generations of climate models to generate intraseasonal variability. For example, where once a model could produce intraseasonal variability the succeeding model might loose this ability. This occurs despite the fact that the new model has a more comprehensive (and realistic) physics package. This suggests a lack of understanding of the fundamental physics that generates observed intraseasonal oscillations. Important new satellite observations are becoming available (e.g., EOS A-train) that are improving our understanding of the basic structure of intraseasonal oscillations. For example, AIRS (Atmospheric InfraRed Sounder) data have revealed shortcomings in the reanalysis representation of the vertical structure of humidity during the life-cycle of the Madden-Julian Oscillation. The roles of other aspects of the hydrological cycle (e.g., microphysics, vertical heating profiles, boundary layer processes, and cloud-radiative interactions) in generating/maintaining intraseasonal oscillations need to be understood. Additionally, the Indian Ocean observing system should contribute to a better understanding of the ocean interaction with intraseasonal oscillations (as well as diurnal and synoptic time scales). Models typically have problems in representing intraseasonal convection over the eastern Indian Ocean. From a modeling standpoint, we should benefit from an understanding of why intraseasonal variability was improved with the incorporation of a 2-dimensional cloud resolving model in a climate model. Similar benefit can derived for very high resolution simulations that have been run on the Earth Simulator. However, computing power is a limitation for sensitivity studies with these models.

Outstanding questions include the role of multi-scale interactions since embedded within the intraseasonal convective envelope are higher frequency super-cloud clusters. Also, the diurnal cycle rectifies on to the intraseasonal variability, particularly during the suppressed phase of the oscillation. Additionally, intraseasonal variability can have an impact on the planetary scale. Mean state errors that impact the simulation of intraseasonal variability include the tendency for a split-ITCZ and too strong of a cold tongue in the western Pacific. It was pointed out that the mean is just the average of the variability suggesting a “chicken and egg” problem. However, non-varying (temporally) flux adjustments that produce a more realistic mean state tend to result in improved intraseasonal variability.

Intraseasonal Variation of the Indian Monsoon and the VASCO-CIRENE Experiment
J.-P. Duvel

The onset and retreat of the boreal summer monsoon exhibit “climatological” intraseasonal oscillations which are related to the seasonal modulation of the monsoon system. Local mode analysis is used to detect and characterize intraseasonal events on an event by event basis. This is especially useful for cases in which a model may have some realistic events, but where these would not be represented in an average mode. The scheme also gives a metric for determining the reproducibility (similarity) of individual events compared to the average event. The methodology also allows the extraction of multivariate patterns based on the spectral characteristics of a large-scale reference parameter.

The local mode analysis indicates the intraseasonal variability to be largest over the ocean. It shows the transition northward and the intensification of intraseasonal fluctuations of outgoing longwave radiation from April to June that characterizes the onset of the boreal summer monsoon. The subsequent weakening and amplification of the intraseasonal signal over the western Pacific is seen from July to September. Rossby wave emanation from the tropics was isolated with the intraseasonal variability being associated with large-scale coupled ocean-atmosphere processes. Cold SST anomalies and strong wind occurred subsequent to the deep convection. It was suggested that the magnitude of the SST anomalies was sensitive to the mixed layer depth, and possibly the ocean surface layer.

The IPSL (Institute Pierre Simon LaPlace) atmospheric model gave a more realistic representation of intraseasonal variability than did the coupled version of the model (CM4). It was suggested that the lack of reactivity of the SST was a contributing cause to the poor intraseasonal variability in the coupled model. Increased resolution of the mixed layer may help capture the rectification of the diurnal cycle on to the intraseasonal time scales. The intraseasonal simulation may also depend on the quality of the mean state, the details of coupling between the ocean and atmosphere, and the surface fluxes.

Time did not permit a detailed discussion of the VASCO-CIRENE Experiment that will make measurements over the western/central Indian Ocean at about 7°S. The experiment consists of 3 observing periods (February 2005, January 2006, and January 2007). During all three observing periods pressurized balloons will make thermodynamic and wind measurements at 850hPa, and the Aeroclipper system will make measurements of temperature, relative humidity, pressure, and winds at 60 m above the ocean surface, and provide sea surface temperature, sea surface salinity, and water speed. The final observing period will be the most intensive, with hourly ocean observations, air-sea surface and radiative flux estimations, frequent radiosonde launches, cloud base and integrated water content measurements, as well as ocean biogeochemistry measurements. Argo floats will provide subsurface data during and in-between the different stages of the campaign. Overall the experiment will allow the investigation of the relationship between convective events, surface fluxes, SST and the mixed layer, and the atmospheric boundary layer on diurnal, intraseasonal time scales, as well as seasonal to interannual variations of the ocean mixed layer structure and ocean equatorial wave dynamics.

Air-Sea Interaction in the Intraseasonal Oscillation
S. Woolnough, J. Slingo, P. Inness, D. Bernie, B. Hoskins, and F. Vitart
A schematic diagram of the relationship between Madden-Julian convection and sea surface temperature, surface fluxes, and winds was shown. The convection is in quadrature with the sea surface temperature dipole. The warm anomalies to the east of the convection are associated with increased shortwave flux at the surface, and below-normal evaporation. To the west the cold sea surface temperature anomalies are associated with enhanced evaporation in the presence of westerly winds, and reduced shortwave flux at the surface due to cloud shielding.

Investigations with an aqua-planet GCM forced with a propagating SST dipole similar to that which occurs during the Madden-Julian Oscillation, indicates the precipitation anomalies are largest for the slower moving SST propagation, while for the faster propagating SST anomalies (30-90 days) the rainfall maximum is shifted toward the center of the dipole. The results also indicate that lower tropospheric moisture variations are important for determining the timing and magnitude of the precipitation maximum. Even so, the surface fluxes are not properly represented since the observed sea surface temperature anomalies arise due to air-sea feedback. Hence, coupled models usually show improved intraseasonal characteristics compared to atmosphere only models. The improvement is contingent upon the model having a realistic basic state. Improvement of the basic state of the HadCM3 model through flux adjustment has given rise to more realistic eastward propagation of convection from the Indian Ocean into the western Pacific. Even so, the sea surface temperature anomalies are too small, thus their impact back onto the atmosphere is too weak. Observations have indicated the importance of the diurnal cycle for warming the upper ocean during quiescent periods, such as during the suppressed phase of the Madden-Julian oscillation. Sensitivity tests with a 1-dimensional ocean model have indicated that 1m vertical resolution and hourly air-sea coupling are required to capture the rectification of the diurnal signal onto the intraseasonal variability. This produces a 40% increase in the warm anomalies that would occur in advance of intraseasonal convection compared to simulations that use 10m vertical resolution (typical of the upper ocean resolution in climate models).

Experiments with the European Center for Medium-Range Weather Forecasts (ECMWF) monthly forecast system for the TOGA-Coupled Ocean Atmosphere Response Experiment (COARE) period were made using persisted SST, a full ocean model (with 10m vertical resolution in the upper ocean), and a mixed layer model (1m vertical resolution). 32-day forecasts were made every day (5 members) and metrics of MJO variability were examined. For these metrics the full ocean model and the mixed layer model both beat persistence with the mixed layer model having the best overall skill. This further suggests that an improved representation of the upper ocean can improve MJO forecasts.

Interactions Between ENSO and the Asian Monsoons
G. Lau

To try to understand the essential mechanisms involved in covariability between ENSO and various aspects of the Asian monsoons, 16 member ensembles were generated using the GFDL R30 model for the period 1950-1999. Observed SST is prescribed in the central and eastern Pacific Ocean, while elsewhere the atmosphere is coupled to a simple (thermodynamic) mixed layer ocean model. The control integrations have SST climatology prescribed outside of the central/eastern Pacific. Poleward of 60^{o} SST climatology is prescribed in all simulations.

These experiments, in conjunction with results from a stationary wave model indicate that during El Nino summers the South Asian monsoon region is under the influence of an anomalous low-level anticyclone that is attributable to the below-normal heating over Indonesia and the western Pacific. This is associated with the displacement of the Walker circulation during El Nino. The Indian Ocean circulation anomalies induce local SST anomalies through the surface heat fluxes, with the SST being above normal during the weak monsoon/El Nino. These SST anomalies persist and feedback to the atmosphere leading to a reversal of the precipitation anomalies the following summer. These results are consistent with the Meehl (1993) biennial mechanism.

During the summer of El Niño events, a low-level cyclonic anomaly is simulated over the North Pacific. This feature is a Rossby wave response to the enhanced condensational heating over the equatorial central Pacific. Advective processes associated with the cyclone anomaly lead to cold temperature tendencies along a zonal belt extending eastward from northern China to the western North Pacific, and negative vorticity tendencies over the subtropical northwestern Pacific. These pre-conditions set the stage for the abrupt establishment of a strong Philippine Sea Anticyclone (PSAC) anomaly in the autumn. The synoptic development during the onset of the PSAC anomaly is similar to that accompanying cold air surges over East Asia. The PSAC anomaly attains maximum amplitude in the boreal winter of El Niño events. The near-surface atmospheric circulation and cloud cover associated with the mature PSAC anomaly affect the local surface heat and radiative fluxes, thereby altering the underlying SST conditions. The ensuing air-sea interactions in turn contribute to maintenance and eastward displacement of the PSAC and SST anomalies in the winter and spring seasons.

The space-time characteristics of the intraseasonal variations (ISV) in the East Asian monsoon region have been examined using extended empirical orthogonal functions. The onset of the PSAC anomaly is coincident with a prominent episode of the leading ISV mode. The air-sea interactions accompanying the ISV in the model atmosphere exhibit a strong seasonal dependence. During the summer, the climatological monsoon trough over the subtropical western Pacific facilitates positive feedbacks between the atmospheric and oceanic fluctuations. Conversely, the prevalent northeasterly monsoon over this region in the winter leads to negative feedbacks between the SST and wind fields associated with the ISV.

ENSO events influence the amplitude of the ISV by modulating the large-scale flow environment in which the ISV is embedded. Amplification of the summer monsoon trough over the western Pacific during El Niño enhances air-sea feedbacks on intraseasonal time scales, thereby raising the amplitudes of the ISV. Weakening of the northeasterly monsoon in El Niño winters suppresses the frequency and strength of the cold air surges associated with the leading ISV mode in that season.

Discussion suggested that the biennial tendency may be due to the prescribed ENSO forcing and that additional model complexity should be considered to establish the role of ocean dynamics. The new Indian Ocean observing system will provide data to assess this question.

Boundary layers and Low-level Jets
C. Saulo and J.-N. Paegle
The relationship between LLJs and deep convection is responsible for a large fraction of the warm season rain. This suggests that LLJs are important contributors to regional climate, particularly in monsoon regions. LLJs act as moisture "pipelines", that fuel regions of heavy precipitation. The classical theories of LLJ were reviewed, and both local effects (PBL oscillations, differential heating over the sloping terrains and land-surface characteristics) and a larger scale forcing (coupling of upper jet streak with LLJ, interaction between LLJ and convection etc.) are important. There is a significant diurnal cycle signature (nocturnal jet) that is mainly related to local effects. Many observational and modeling studies suggested that the LLJ is basically explained by PBL mechanisms including differential heating over sloping terrain and/or with topographical boundaries. However, these interactions cannot fully explain the observed low-level wind behavior, namely, why are winds in the core of the LLJ considerably stronger than at the boundaries. It seems clear that upper-level synoptic waves develop a favorable environment for LLJ formation. In this environment, precipitation (large-scale convection) also plays a significant role in the LLJ intensification.

As for the predictability of LLJ, PBL-related features of the LLJ are more predictable than the highly non-linear interaction between the LLJ and the organized convection at its exit region. Parameterization of convection may be a critical factor for the correct representation of the LLJ, especially since the diurnal cycle of precipitation is poorly represented by current models. However, the interaction between convection schemes and the boundary layer scheme may be critical to address this problem. An improvement in turbulence treatment and incorporation of information about soil moisture, surface evaporation, vegetation type and high-resolution topography are likely to improve the ability of regional and global models to forecast the development of the LLJ. The linkage between the LLJ and mesoscale convective systems implies that an improved simulation of the LLJ is likely to improve forecasts of nocturnal thunderstorms and consequently better represent a significant amount of the summer precipitation.

Role of Land Processes and Fluxes
J. Polcher
The Charney hypothesis (Charney, 1975) is a starting point for land-atmosphere interaction that was developed to suggest how overgrazinig could explain decreasing precipitation over the Sahel. It focuses on positive feedback of increased surface albedo due to overgrazing that result in a decrease of radiative heating over the continent. Compensation of the reduced radiative heating is through the dynamics which results in increased subsidence over the continent and a further reduction in precipitation. However, the surface energy balance is also sensitive to evaporation characteristics, surface roughness and heat capacity etc. The monsoon is a succession of singular events, and the surface energy balance responds to these events. Tropical (and monsoon) climates can be characterized by an alternation of strong convective and subsidence events, and surface changes can impact both components differently. For example, the evaporation is very sensitive to soil moisture, so surface fluxes are sensitive to rainfall, and they can impact subsequent events.

There is uncertainty in land/atmosphere interaction in GCMs (e.g., a deforestation can induce both reduction as well as increase of moisture convergence due to different changes in surface properties). In order to intercompare the sensitivity of models one needs to apply exactly the same perturbation to all GCMs, and such a design was proposed by the GLACE project. The results using 12 different models show that three semi-arid regions (India, West Africa and the Great Plain of North America) are critical regions where land-atmosphere coupling (evaporation to rainfall signal) is strong. In these critical regions the evaporation signal is transmitted into precipitation via various parameterizations of atmospheric processes.

Some intensive airborne and satellite observations suggested positive feedbacks of land-atmosphere interaction through PBL processes in synoptic and mesoscale surface perturbations. Models may need to have the right surface-atmosphere interactions to reproduce these feedbacks. These surface hotspots produce higher atmospheric temperature, lower pressure and subsequent circulations and rainfall. In this context, irrigation may have an impact on regional rainfall and hydro-climate through avoiding the formation of hotspots. To study this, land surface models need to have the ability to simulate irrigation. A 15-year simulation of the Indian subcontinent by the LMDZ model when irrigation effects were included showed some increase of monsoon rainfall and moisture convergence. To summarize,

1) We do not yet have right tools to answer the questions on the impacts of land use on the monsoons raised since J. Charney's pioneering work.
2) Our models should have all the right ingredients but they do not provide yet a trustworthy description of the surface atmosphere interactions.
3) Our understanding of the mechanisms involved is insufficient to validate or improve the sensitivity of these models.
4) Insufficient attention has been paid to the interactions between the parameterizations of the models and their ability to describe the feedbacks over all time scales.
5) The monsoon regions are data poor and thus do not yet support detailed process studies. Hopefully, AMMA will change this!

Diurnal Cycle of Convection and Its Impacts
J. Slingo

The diurnal cycle is important because (1) it is crucial for land surface energy and water budgets, (2) it influences the mean climate through local and remote effects, (3) it potentially influences the structure and evolution of the upper ocean, (4) getting it right is a stringent test of the physics of models, and (5) its changes (e.g. in diurnal temperature range) may be key impact/indicator of climate change.

The local time of maximum precipitation in observations and models are quite different: over oceans it tends to occur between 10am-noon in observations, but between midnight and 4am in models, and over land it is 6pm-10pm in observations, but midday in models.

Many conceptual models of tropical convection are based on a BIMODAL cloud distribution, emphasizing shallow "trade-wind" or boundary layer cumuli and deep cumulonimbi, but TOGA COARE results emphasize the dominance of cumulus congestus and point to a TRIMODAL cloud distribution in which the freezing level inversion is the key. Over the oceans cumulus congestus clouds are most prevalent during light wind conditions in the presence of a strong diurnal cycle in SST. These clouds occur most frequently in the late afternoon, suggesting that they are triggered by the diurnal cycle in SST.

Over the Maritime Continent large model errors in the diurnal cycle of convection are prominent. Complex land/sea breezes organize convection of 100 to several 100 km scales indicating that subgrid scale land/sea breezes may be crucial for estimating the energy and hydrological budgets of the Maritime Continent. Land/sea breezes have two major impacts: (1) convergence along the sea breeze front provides additional convective mass flux, and (2) winds associated with land-sea breezes enhance surface fluxes leading to increased moisture supply.

In many monsoon regions, the phase of the diurnal cycle shows systematic propagation of the convective signal away from the coast (e.g., over Bay of Bengal, off the Mexican Peninsula, the Maritime continent), presumably as shallow or deep gravity waves associated with land/sea breezes. A simulation by a mesoscale models (MM5) over the Maritime continent showed a system of propagating land-sea breezes where precipitation is generated over the ocean during the early morning by the convergence initiated by the land breeze, and orographic effects enhance the land breeze.

In conclusion, several issues on diurnal cycle are raised as follows:

1) The diurnal cycle may be an example of non-equilibrium convection.
2) If we can improve the diurnal cycle, are we able to improve the MJO?
3) Sub-gridscale triggers of convection may be important for the diurnal cycle. Stochastic physics may help for this.
4) Multi-scale effects of convection may be important for producing the mean climate.
5) How to use CRMs and RCMs to improve the diurnal cycle is a key.

Soil Moisture – Precipitation Feedback and the Diurnal Cycle in GCMs
D. Lawrence

Soil moisture – precipitation feedback is one of the most important processes governing hydroclimate variability in monsoon regions. The definition of this feedback may be taken as the extent to which a precipitation-induced soil moisture anomaly influences the overlying atmosphere and thereby the evolution of weather and the generation of precipitation. The GLACE project tried to diagnose and quantify this feedback in 12 GCM models, by introducing land-atmosphere coupling strength (refer to the report of J. Polcher)

The soil moisture-precipitation feedback, which is diagnosed in GLACE to be strong in monsoon regions, is very weak in HadAM3-MOSES2 and very strong in CAM3-CLM3. This occurs despite the finding that the soil moisture – evaporation relationship is roughly equivalent, at least in magnitude, across the two models. An indirect soil moisture – precipitation feedback, supported from FIFE (First ISLSCP Field Experiment) observations, may be responsible for the difference of the two models. That is, over wet soil surface, a hydrological loop of enhanced evaporation → lower Bowen ratio → shallower and wetter boundary layer, combined with a thermodynamic loop of darker soil ($\alpha \Downarrow$) and cooler surface temperatures → enhanced net surface radiation → larger total heat flux into boundary layer which may increase moist static energy per unit mass of boundary layer air.

A clear difference between the models is that the CAM3 boundary layer simulates a differential diurnal build-up of moist static energy and a shallower boundary layer over wet vs. dry soils. These features are absent in HadAM3. The very early onset of convection and early maximum of rainfall in HadAM3 is likely complicit in the weak land-atmosphere coupling. The early onset of convection may itself be related to weak boundary layer entrainment.

These results point clearly to the need for longterm observational time series of soil moisture, fluxes, and boundary layer properties in varied climates (AMMA, NAME) and more integrated process studies on the intricately coupled land surface – boundary layer - convection problem.

GCSS and Its Potential Role in Improving Monsoon Prediction
C. Jakob

An overview of current GCSS activities was given. Among the six active working groups, four (PBL clouds, cirrus, deep convective cloud systems and Pacific cross-section model intercomparison) are directly relevant to monsoon studies. The group investigating deep convective cloud systems aims to simulate active and suppressed conditions and the transition between them using a hierarchy of models, including CRMs, RCMs, and GCMs (www.convection.info). Extensive analysis of the TOGA/COARE period is planned during which three strong MJO events occurred. As an example of monsoon and tropical cloud system study, cloud regimes as identified in ISCCP exhibited substantial changes associated with active and suppressed conditions of the ISO over the western tropical Pacific and the Bay of Bengal. The Pacific cross section intercomparison investigates cloud system change across NE to SW Pacific extending from the deep convective clouds zone to the strong subsidence zone. DIME (Data Integration for Model Evaluation) plays a role of one-stop shop for modelers using GCSS data and information (http://gcss-dime.giss.nasa.gov/).

A view of the model development process suggests how GCSS and CLIVAR can interact with each other. The key is to identify common problems that can be investigated in a collaborative fashion. Upon the selection of the relevant case studies, and others like it, is a better understanding of processes that then leads to refined parameterizations. The new parameterization can then be tested and assessed in NWP and climate simulations.

Key Issues for Parameterization of Convection in the Monsoon Regime
D. Randall

Key issues for parameterization of convection in the monsoon regime are reviewed, including discussion of how to solve them. The issues may be summarized as follows: (1) over land, monsoon convection is strongly influenced by surface energy fluxes, (2) there is a strong diurnal component, and (3) interactions of deep monsoon convection with the boundary layer are paramount. Although the interaction with deep convection is one of the most important "jobs" of the PBL, it has been neglected by modelers. The one exception may be the Arakawa-Schubert (AS) parameterization which has been shown to simulate the afternoon peak in convection that occurs over continental North America. AS included an explicit PBL sub-model, convective inhibition (PBL-top inversion, etc.) and both shallow and deep convection. However, important interactions were left out including downdrafts, bubble variability (including thermodynamic properties, diameter etc.), unmixedness, surface-flux enhancement, deep convection that starts above the PBL, and orographic effects.

Large-eddy simulation (LES) of cloud formation based on TRMM data over the LBA region suggested that evolution of PBL related to surface diurnal heating is essential for bubble variability and organization of cumulus cloud ensembles. A similar feature was suggested in a previous GCM study using AS but with an assumption that the minimum λ (entrainment rate) depends on inverse number of the PBL depth (Tokioka et al., 1988).

Realistic simulation of the diurnal cycle in convection and rainfall is a big challenge in the tropics and monsoon region. The super-parameterization better represents the diurnal cycle over the LBA region. Some inferences are; (1) a simple PBL model that is explicitly coupled to deep convection can give a realistic diurnal cycle of precipitation over both land and sea, and (2) to go further, we may need to simulate the thermo-dynamic variances in the PBL, which are strongly affected by precipitation.

To solve these issues, we may need a unified parameterization of PBL turbulence and shallow/deep convection, which can well represent processes of both advection and diffusion in PBL depth tendency. Advection may be essential for deep (penetrative) convection, while both processes are necessary for shallow convection. Some recent papers (e.g., Randall et al., 1992; Lappen and Randall, 2001) partly succeeded in doing so, though we need further effort for deep convection.

Regional Modeling of Monsoons
Y. Wang

The principal use of RCM's is to downscale coarser resolution observations and models. Presently, nesting is one-way such that the RCM does not feedback to the larger scales, such as when using lateral boundary conditions from a global model or reanalysis. RCM's enable the better resolution of complex topography, land surface properties, mesoscale circulations, low-level jets, the Mei-yu and Baiu fronts, and land-sea interactions resulting in improvements of the mean and variability over the regional domain. The monsoon domain is dominated by topographically anchored precipitation centers, including those adjacent to the western Ghats, the foothills of the Himalayas, Burma, and large islands of the western Pacific (e.g., the Philippines). These locations are also where the interannual variance of rainfall is large. These regions of steep topography are poorly represented in GCMs.

RCM model simulations demonstrated (1) the ability to capture severe precipitation events over China including the rapid seasonal frontal transition and the spatio-temporal variations of rainfall, and the frequency of occurrence of extreme rainfall events, (2) the inability to simulate the fine structure of convection related to mesoscale mountains leads to biases in the large-scale circulation and precipitation, and (3) identifying uncertainties in physical parameterizations. Improved oceanic precipitation was obtained with a modification to deep convection and changes to the relative humidity threshold criterion for convection.

Issues to be considered include (1) the relative merits of further increasing spatial resolution versus more accurate physics, (2) determination of an optimal domain size for RCMs, (3) development of techniques to better compare model and station data, and (4) the need for ensembles of RCM simulations for testing initial condition sensitivity and for detecting climate change.

Future directions include (1) evaluating the performance of RCMs relative to GAME and CEOP data, (2) identify feedback processes in the monsoon such as those related to the diurnal cycle of clouds and precipitation (e.g., the RAIME project), (3) to evaluate the impact of high frequency weather and mesoscale signals on the large-scale flow and its impact on the mean and variability (upscaling; two-way nesting), and (4) develop regional coupled ocean-atmosphere models to evaluate the impact of air-sea interaction on monsoons. It was suggested that regional climate modeling might be better organized through the establishment of a WCRP Regional Climate Modeling Panel to evaluate progress and define future goals.

Modeling and Predicting Monsoon Variability

P. Webster, C. Hoyas, P. Agudelo, J. Curry

Strategic versus tactical decisions need to be made when it comes to monsoon prediction. Present dynamical models, including those used in NWP, exhibit large systematic error in their ability to represent the monsoon. Their error growth saturates in a few days, in many cases the error is larger than the signal one is trying to predict. Dynamical models have difficulty simulating the development of intraseasonal oscillations, including the destabilization stage (preconditioning of the atmosphere in advance of the deep convection), the strength of the convection, and the transition to the suppressed phase.

The immediacy of the need for subseasonal (intraseasonal) forecasts of the monsoon is paramount and cannot wait for better dynamical models to be developed. We have developed a method of forecasting the slow-manifold using a wavelet technique so as not to contaminate the statistical correction across different time scales. This is applied to ensembles of forecasts made with the ECMWF model. Forecasts for different regions of the Asian summer monsoon domain have been very successful, and forecasts for other regions (N. and S. America) are being planned. For example, forecasts of the Ganges-Brahmaputra river discharge have been successful at 1-6 month lead times. The forecasts of river discharge are also presented in probabilistic terms of an exceedance danger level for disaster management. With shorter lead times (including those associated with intraseasonal variability), the forecasts provide information useful for crop selection and planting times.

Metrics from the empirical forecast scheme can be used for gauging improvement of the dynamical models by determining where and how the two forecasts deviate. An important aspect is to understand the impact of error growth, for example by fast time scales associated with convection, and how this impacts the slower intraseasonal manifold. More insight is to be gained from examining data obtained during TOGA-COARE and the Joint Air-Sea Monsoon Investigation (JASMINE). Understanding of the hydrological cycle must be improved, including during the suppressed phase of intraseasonal variability.

Development of a European Multi-Model Ensemble System for Seasonal to Interannual Prediction (DEMETER)

T. Palmer

Seven coupled ocean-atmosphere GCMs have performed 6 month hindcasts from four start dates for each year over the period 1980-2001. Nine member ensembles were generated from perturbations to SST and winds from ECMWF Reanalysis (ERA)-40 initial conditions. The skill of the ensemble mean was substantially greater than that for an individual model as demonstrated for NINO3 SST and monsoon zonal wind shear indices. Reliability diagrams (Relative Operating Characteristic-ROC) for tropical temperature and precipitation clearly demonstrated that the multi-model ensemble skill exceeded that of any individual model. Similarly, the time-mean rainfall bias was lowest for the ensemble mean. Comparison in which the same atmospheric model was used with different ocean models indicated that the atmospheric model is the dominate cause of precipitation errors.

Despite this success, there are still shortcomings in the multi-model/multi-parameter representation of uncertainty. Two approaches to this problem include stochastic parameterization and cellular automaton stochastic backscatter schemes (CASBS). In CASBS rules need to be established to be consistent with the prevailing meteorology. Sensitivity tests with a T799 version of the ECMWF model using CASBS produces the k-5/3 energy spectrum not captured in the standard model configuration. This also results in a reduction of systematic error of seasonal mean rainfall. Other applications include the representation of eastward propagating intraseasonal variability in which westward propagating supercloud clusters are embedded. It is suggested that a computationally cheap stochastic-dynamical model could provide specific realizations of subgrid motions rather than the more traditional ensemble mean of subgrid effects. ENSEMBLES, the successor project to DEMETER, will intercompare the performance of multi-model, perturbed parameter, and stochastic-dynamic parameterization in coordinated seasonal and decadal time scale integrations. As such it will provide input to the WCRP COPES initiative.

CCPP ARM Parameterization Testbed: A Paradigm for CEOP

G. L. Potter

CAPT fosters collaborations between GCM developers (e.g. in CCPP) and parameterization specialists (e.g., in ARM), of which goals are to provide diagnostic assessment at ARM sites and globally for climate models run in NWP mode using the best data available for clouds, radiation, and moist processes, and to work with parameterization developers to test their schemes and suggest improvements that result in better models (one of the goals of this meeting). The tasks of CAPT include (1) use of NWP techniques to assess climate models (at climate model scales), 2) isolation of parameterization errors before feedback obscures source of errors, (3) comparison with detailed observations, (4) working with parameterization developers, (5) testing models in climate mode, and finally (6) improving models! This CAPT approach fits nicely with one of CEOP's missions to determine: "how the representations of land-surface processes in both global and regional climate models affect the precipitation and hydrologic predictions."

Some good examples are described as follows: CAM2 forecasts of precipitation coincide with observations in boreal spring (frontal precipitation), but not in summer (convective precipitation) at the ARM/SGP (Southern Great Plain) site. Vertical error structures are seen in composites of 5-day forecasts of relative humidity (RH) for June/July of 1997 and 10-year climatology. Diagnoses on atmospheric moisture and temperature tendencies in CAM2 forecasts at the ARM/SGP site show that spurious lower-level drying and upper-level moistening is mainly associated with the Zhang deep convective parameterizations (Williamson et al., JGR 2005). The new Zhang' parameterization was introduced to the model which resulted in improvement of temperature and water vapor profiles and the simulation of precipitation. In CAM2 June/July forecasts modification of the convective available potential energy (CAPE)-based convective trigger criterion to one that includes dynamics favorable for convection (DCAPE-based criterion) improved local and global-scale patterns of convection and precipitation (Xie et al. 2004).

c. Invited Presentations: Modeling and Predictability Efforts

Modeling the Monsoon System

C. R. Mechoso, H.-Y. Ma, I. Richter, G. Cazes-Boezio, C. S. Konor, A. Arakawa, Y. Xue, R. Terra, and M. Mendina

The American monsoon systems are characterized as being dominated by convection over land with subsidence to the west. The diurnal cycle over Amazonia was evaluated. Observations and a CRM indicate that the maximum rainfall occurs between 1-3pm local time. The CRM result indicates that turbulent moisture convergence at the top of the planetary boundary layer (PBL) causes the PBL to deepen throughout the morning. Despite the early afternoon precipitation, the PBL continues to deepen into the late afternoon via the turbulent transport of water. A recent version of the UCLA GCM adds vertical levels to the PBL captures better these processes. The increased resolution permitted resolving smaller scale eddies and gave rise to a realistic diurnal cycle of rainfall over Amazonia compared to the earlier version of the model in which the PBL was the first layer above the surface. The simulation with the increased resolution in the PBL also exhibited an improved northwest to southeast tilt of the South Atlantic Convergence Zone. An added benefit is that in the subsidence region to the west SST errors over the stratocumulus regions have been reduced. However, the "double ITCZ problem in the Pacific still persists. Two hypotheses for this problem were proposed: (1) that it is related to poor heat transport by eddies from upwelling regions; suggesting that the ocean model may have insufficient resolution, (2) poor representation of the zonal circulation due to poor simulation of resolved and subgrid processes in the atmosphere.

On a monthly time scale the model precipitation was found to be sensitive to vegetation processes. Over South America a simple two-layer soil model gave rise to an overestimate of rainfall compared to an explicit vegetation model.

The simulated boreal summer monsoons over Africa and Asia are too wet compared to observations. Links were suggested between these model difficulties.

In terms of model metrics of success in monsoon simulation it was suggested that the focus should be on processes rather than particular fields, and that AGCM verification requires coupling the model to an OGCM. For the diurnal cycle the PBL needs to be evaluated in detail, including vertical profiles of potential temperature, moist static energy, total and liquid water vapor, turbulent fluxes, etc. Evaluation of the interaction between the PBL and the free atmosphere is essential, including entrainment at the top of the PBL, and links to convection and downdrafts, etc. For the general circulation a better understanding of the zonal circulation and the processes that govern it is required. Also, convection and radiation including the vertical distribution of heating and their relationship to the dynamics need to be evaluated. It was stressed that an integrated analysis of the Earth's monsoon systems is required on a hierarchy of time and space scales, and not just for the convective component.

Indian Monsoon Prediction in the NCEP Climate Forecast System (CFS)

S. Lord, S, Saha, C. Thiaw, and D. Stokes

The National Center for Environmental Prediction Coupled Forecast System (NCEP CFS) consists of a T62 L64 version of the atmospheric model used in the global forecast system coupled to the modular ocean model (MOM)3 L40 without the use of flux adjustment. This configuration is used for seasonal to interannual climate forecasts. The atmospheric (oceanic) initial states are taken from the NCEP/Department of Energy DOE) Reanalysis-2 (NCEP Global Ocean Data Assimilation). This version of CFS became operational in August 2004. Nine month forecasts have been made for each month with 15 member ensembles for 1981-present. For this presentation 5 member ensembles based on different atmospheric states for 9-13 May 1981-2004 have been generated. As an example of skill the forecasts of NINO3.4 SST anomalies improved relative to the previous version of the model and now exceed canonical correlation analysis, constructed analogue, and other statistical forecasts.

Pentad data are used to study the boreal summer Indian/Asian monsoon. Major timing and interactions between wind, SST and precipitation fields and geographical variations are captured by the CFS and there is some predictability in aspects of the wind and precipitation fields over the Southeast Asia domain, including India and the Maritime continent. Nevertheless, critical examination of all fields reveals some weaknesses which need to be diagnosed and addressed. In the vicinity of the Somali Jet and over the Bay of Bengal the 850hPa winds in CFS are too weak compared to NCEP/DOE Reanalysis-2 throughout the monsoon season. Despite this, CFS overestimates rainfall along the western Ghats and from Burma to the Himalayan foothills. Over the Indian subcontinent the rainfall is underestimated in CFS. The Somali jet strengthens 1-2 pentads later than observed, and thus there is a concomitant delay in the onset of monsoon rainfall over India. In terms of anomaly correlation, little if any skill exists over India in June-August, while the model is more skilful over the Maritime continent. It is not known why this occurs in the model. With the too weak winds over the Arabian Sea the forecast SST is too warm, though a similar signal over the Bay of Bengal is not manifest. In both observations and the model the tendency is for the strongest 850hPa winds over the Somali Jet region to lag the all-India rainfall. However, over the Bay of Bengal the relationship of the strongest winds relative to all-India rainfall is not captured.

The NOAA Climate test bed will host CFS data and software to promote further investigations of the performance of the seasonal to interannual prediction system.

Modeling and Predictability Issues Related to East Asian Monsoon

M. Kimoto

Compared to the medium resolution (T42) version of the MIROC GCM, the high resolution (T106) version gives a superior representation of the Mei-yu and Baiu fronts, the extratropical jet and the Okhotsk high pressure system. Improvement also occurs for the probability distribution of rainfall rate over Japan, and the spatial pattern of rainfall occurring in extreme events (50mm day^{-1} or greater). Over the equatorial Indian Ocean, only the high resolution model captures the poleward bifurcation of convection that occurs on intraseasonal time scales.

Physics also had an influence on the ability to represent tropical convection. Including a critical threshold for relative humidity before convection can occur gave rise to more realistic eastward propagation of convection in the near-equatorial region. This resulted in a better simulation of the tropical wave spectra and the relationship between convective available potential energy and precipitation.

Extratropical wave activity is linked to interannual predictability over East Asia. Boreal spring surface air temperature anomalies over Eurasia influence blocking over East Siberia during early summer. In winter northern Japan temperature is correlated with the Artic oscillation.

Elements about the Development of Climate Models in Europe

H. LeTreut

In Europe, great efforts in model development have been put forth to implement new models for the Intergovenmental Panel on Climate Change Fourth Assessment Report (IPCC AR4). This development and the computer time devoted to the IPCC simulations were performed at the expense of doing other scientific works, including process and sensitivity studies. Model development is moving toward an Earth Systems Modeling approach with the inclusion of chemistry, the carbon cycle, and a more complete treatment of aerosols.

The latest version of the Laboratoire de Meteorologie Dynamique/Institute Pierre Simon LaPlace (LMD/IPSL) GCM contains revised schemes of convection, the planetary boundary layer, clouds, and the land surface model. Compared to an earlier version of the model there is a general improvement in the tropical circulation, but no improvement in the Indian monsoon. The mean and seasonality of the SST has improved. Stretched grid versions of the model are used to put high resolution over regions of interest. The four configurations are for Europe, India, AMMA (Africa), and CLARIS. These versions are used for cyclone predictions, as well as parameterization testing in relation with instrumented sites.

The United Kingdom Met Office model, HadGEM1, differs extensively from the previous model, HadCM3. Some of the modifications include a non-hydrostatic treatment with semi-Lagrangian advection, non-local mixing for unstable boundary layers, prognostic mixed phase microphysics, a revised convection scheme, a new land surface model, and an interactive sulfur cycle and aerosols coupled to a new ocean model. The boreal summer monsoon circulation at 850hPa has improved over the Arabian Sea, Indian Ocean, and the Bay of Bengal, but the westerlies extend too far to the east associated with a lack of convection over Indonesia. The precipitation is improved over the central and equatorial Indian Ocean, and over the western Ghats. However, that over the Indian subcontinent is less well simulated. Atmosphere-only and coupled versions have similar and realistic dominant interannual modes, but they are overly strong. The coupled model has more realistic equatorial eastern Indian Ocean variability which might be due to an improved Indian Ocean dipole. Anomalies in ENSO years are realistic, but internal variability tends to dominate.

A European Union project (EUROCS-EUROpean Cloud Systems) will aim to improve the representation of cloud systems in global and regional models. They will use a hierarchy of models, including GCMs, single column models, cloud resolving models, and large-eddy simulations to improve deficiencies related to stratocumulus over the ocean, the diurnal cycle of cumulus, the diurnal cycle of deep convection over continents, and the sensitivity of convection to differing moisture profiles.

5. Working Group Summaries

a. Group A: Strategy for Parameterization Development and Observational Data Requirements (Chair: J. Polcher)

Key Process Issues for Monsoons:
The group members agree that parameterization development requires a long-term sustained funding commitment from the agencies. Such a commitment, however, is not currently available in most countries.

Monsoon regions are locations of complex interactions and no specific parameterization could be identified as the key problem in models, and therefore, monsoon regions are not necessarily ideal for developing parameterizations because of the complex scale interactions. On the other hand these are good regions for the evaluation of parameterization. It was also agreed that the interaction between parameterizations is probably the problem most critical in the monsoon regions and this should be the focus of our attention.

Potential Ways Forward:
Process studies yield the promising prospect to improve the interaction between parameterizations. The group recommended the process studies in two categories:

1st order processes studies:
- Land-surface atmosphere interactions
- Vertical distribution of diabatic heating
- Upper-layer ocean atmosphere interactions

2nd order processes studies:
- Aerosol effects
- Land hydrology, including snow cover/mass, rivers, aquifers, flooded areas etc.

WCRP/CLIVAR/GEWEX Mechanisms to Address These Needs:
The group suggested near-term and medium-term actions for CLIVAR/GEWEX collaborations as follows:

Near term:
- Focus on diurnal to intra-seasonal timescales
- Increase use of CAPT experiments, model nudging or regional model studies
- Communication between GMPP groups and CLIVAR modeling groups on these process studies
- Make better use of existing data and support current data integration efforts

Medium term:
- Raise the profile of model development and promote funding
- Improve the observational network in the monsoon regions for validation of models
- Field campaigns to support process studies

What Cannot be Addressed:
Some issues may need more time before addressing if the approach is "Don't run before you can walk." For example, Decadal variability of monsoons can not be addressed as long as the general representation of the monsoon in models is not improved.

How Can CLIVAR and GEWEX Better Coordinate?
The group recommended that WCRP have a monsoon panel/working group within the COPES initiative. This should include a strong participation of modelers and model developers.

b. Group B: Strategy for System Modeling and Observational Data for Large-scale Model Validation
(Chair: K. R. Sperber)

Key Process Issues for Monsoons:
Based on the workshop presentations, and discussions of ongoing research of the Group B members, improvement of the diurnal cycle of rainfall in global models is the primary effort that CLIVAR and GEWEX should address in the near-term. The diurnal cycle is a forced "mode" of variability that is seen as a stumbling block toward an improved representation of monsoon systems and their variability and predictability. Key process issues that need to be addressed include convective triggering, the evolution of moisture in the planetary boundary layer (PBL), energy, water, and momentum budgets, and the evolution of clouds.

With the poor representation of the diurnal cycle of rainfall, the models are not properly representing the evolution and the energy and water cycle in the tropics. Additionally, cloud radiative forcing is not represented properly which in turn affects the surface fluxes leading to incorrect air-sea interaction. Through multi-scale interactions these shortcomings may in turn affect the ability of models to generate medium-range monsoon variability (e.g., tropical depressions that contribute of significant portion of the seasonal mean rainfall), as well as simulating the active and break cycles associated with intraseasonal oscillations. Thus, the organization of convection and the coupling between the dynamics and physics need to be explored more fully, including the feedback to the large-scale flow.

It is envisioned that focused experimentation (or at least intercomparison) between global models (including those using stretched grids) and regional climate models will help determine if there is a minimum horizontal resolution that may be required to represent the diurnal cycle of rainfall and the above processes. This also provides an avenue to address the importance of orographic forcing of convection and its impact on the circulation. Increased horizontal resolution alone may not be a sufficient condition for improving the diurnal cycle of rainfall. Thus, evaluation of the relevant physics (possibly parameterization of mesoscale downdrafts, convective triggering) employed in RCMs and CRMs that contribute to their more realistic representation of the diurnal cycle of rainfall needs to be evaluated. Essential physics needs to be parameterized in a form compatible for global models, and experiments carried out to assess improvement will be required, including the impact on the physics package as a whole.

In the medium-term, the role of land-atmosphere coupling needs to benchmarked against observations. The necessary observations for model evaluation need to be defined and obtained via GLASS and GLACE. A key observationally based effort is AMMA, which will provide unprecedented data for the study of the African monsoon. Similarly, the role of the ocean (mixed layer in particular) and its affect on the atmosphere needs to be assessed more closely. For the Indian Ocean the 2006/2007 VASCO/CIRENE observational campaign will contribute to our understanding of upper ocean atmosphere interactions, including the role of ocean dynamics, on diurnal, subseasonal, and seasonal time scales. In particular this will aid in quantifying the rectification of the diurnal cycle onto the intraseasonal oscillation. It will also provide new insight into the behavior of the quiescent tropics, and its transition to a convectively active state (e.g., MJO: suppressed to active phase). The role of aerosol and dust, and its impact on the development of monsoon precipitation is an issue to be addressed, though it is considered to be of secondary importance compared to errors in the basic structure of monsoon simulations. Other issues of interest include the impacts of land-use and water-use change which can be facilitated through closer interactions with the Global Water System Project.

Predictability Issues:
Here we note issues that affect predictability. Simulated rainfall on both intraseasonal (boreal summer) and interannual time scales (ENSO forced) is too zonal, that is the models tend to lock onto

the Hadley component of the circulation rather than the Walker circulation component. Diagnostics, such the momentum budget, may be useful for isolating this shortcoming. Determining the initial state of the ocean is a challenge given the relatively sparse observing system in comparison to the atmosphere. Directly impacting the interannual teleconnections is the quality of the ENSO forecasts in terms of amplitude and location of sea surface temperature anomalies. Interfacing with CLIVAR WGSIP and the Pacific Ocean panel is recommended. Also affecting remote teleconnections is the vertical structure of the heating profile due to convection, as well as the relative influence of local vs. remote SST forcing. The simulation of the equatorial cold tongue, as well as the western boundary currents, needs to be improved. The latter problem may in part be related to errors in land-atmosphere interactions and systematic error of the extratropical atmospheric circulation as well as insufficient horizontal resolution in the ocean. A better understanding of the heat transport due to eddies is required, perhaps through an intensive observation period. In the Atlantic, the tropical SSTs are poorly simulated, with most models having the wrong east-west gradient near the equator. Boundary conditions over land are also problematic since information regarding soil moisture, snow cover, and snow depth are not well observed quantities. Additionally, the climate system is inherently non-stationary such that low frequency modes (e.g., decadal) of variability may result in the waxing and waning of statistical relationships that are manifest on shorter time scales (e.g., the monsoon-ENSO relationship weakened in the 1990's-though the cause of the breakdown of this otherwise robust teleconnection is not certain). Extratropical interaction with the tropics may be a limiting factor to monsoon predictability. An established interaction is cold surges that emanate over Eurasia, affecting the weather (surface temperature in particular) over China and eastern Asia, which can extend into the equatorial region and give rise to westerly wind bursts that can influence equatorial wave dynamics. A more recent finding is that the North Atlantic Oscillation has an interhemispheric effect by perturbing the monsoon circulation over South America, though the mechanism(s) of this interaction need to be explored. Stratosphere-troposphere interactions are a potential source of perturbation to the monsoon.

Statistical and empirical predictive methods are in place (and can be expanded to other regions) that can be used as metrics for dynamical forecast improvement. Additionally they may contribute to improvement of models by the relative emphasis they place on the hierarchy of dependent variables used to make the prediction.

Potential Ways Forward:
Testing the spatial and temporal resolution and physics dependencies for the diurnal cycle and for multi-scale interactions represents a "Grand Challenge" problem to the modeling community in terms of scientific effort and computing. Also included in this challenge are sensitivity experiments to isolate important key processes and the evaluation of alternative model formulations such as the super-parameterization, and stochastic physics. Additionally, a better understanding of why multi-model ensembles tend to be more skillful than the individual models needs to be explored. New theoretical studies are needed to develop a new generation of parameterizations, especially for convection. Empirical studies using new metrics for understanding processes are essential.

For predictability, RCMs have limitations due to their requirement that lateral boundary conditions need to be supplied, in which case they are useful for downscaling forecasts. Alternative nesting techniques (two-way interaction with the host model) could help in understanding scale interactions and energy transfer across different resolved scales.

WCRP/CLIVAR/GEWEX Mechanisms to Address These Needs
In the near-term it is envisioned that progress can be facilitated through targeted workshops that would be held in conjunction with pre-existing panel meetings. As noted above, the diurnal cycle, of precipitation in particular, is a common theme that emerged as the leading candidate for attention. Depending on timing, a diurnal cycle workshop could be held in conjunction with the "Workshop on Systematic Model Error" that is currently being planned. However, if necessary, other venues,

including the Georgia Institute of Technology, will be considered. Other topics for targeted workshops might include mesoscale convective systems and/or multi-scale interactions. It is recommended that the various monsoon panels generate a list of priorities for investigation that would be facilitated through CLIVAR/GEWEX interactions.

In the medium-term, focused workshops that address model shortcomings related to predictability, and those to exploit newly obtained observations are warranted (see Section 1b).

What Issues are Barriers to Progress?
Technical barriers include (1) lack of adequate computer facilities for the sensitivity testing required to better understand the model representations of complex processes and their feedbacks. (2) The decay of the observational network needs to be reversed, and the network expanded into regions where observations are scant. (3) Support for model and parameterization development needs to be sustained by funding agencies.

Scientific barriers include (1) the lack of fundamental understanding of the consequences of introducing greater model complexity which may be exacerbated as the models evolve into more comprehensive Earth system models. (2) Theoreticians to better understand model errors (e.g., zonality of signal in models etc.), and (3) needed observations to better represent and parameterize land atmosphere interactions, ocean atmosphere interactions, and properly represent the roles of aerosol and dust.

c. Group C: Monsoon Prediction and Required Observational Network
(Chair: T. Yasunari)

Key Issues in Modeling and Prediction
i) Scientific Issues
The main target of prediction may be intraseasonal variability (ISV) to seasonal cycle (SC), which are fundamental components of monsoon systems. However, simulation of these variations is still unsatisfactory in most of the models. Limits in simulation/prediction exist both in ISV and SC, because ISV rectifies into seasonal mean state. Errors in simulating SC or the mean seasonal state, in turn, degrade ISV, and interannual variations, including the monsoon-ENSO teleconnections. SC is not even reproduced in the current reanalysis data.

Predicting precipitation needs high-resolution (of 10km or less). However, it is not just a resolution issue, and it is likely to depend on parameterization of clouds, which is closely linked to spatial resolution. In conjunction with this, resolving the diurnal cycle (DC) of convection and PBL development is crucial for this issue.

In a larger perspective, the simulation and prediction of the hydrological cycle is essential for predicting precipitation. In many different models the dynamics is similar, but features in hydrological cycle and the scales of organized convection are vastly different. This may partly be related to differences of initial as well as boundary conditions in the atmospheric moisture distribution. Related to this, enormous problems remain in treating land and ocean surfaces, atmospheric moisture, and ocean subsurface conditions, which have great impacts on ISV prediction (where dynamics tightly coupled to convection/surface fluxes) and coupled seasonal prediction (convection/winds coupled to SST anomalies).

Geographically, simulations in the warm pool region (i.e., the equatorial eastern Indian Ocean and the western Pacific) are still poor. This is not a local problem, but may have global impact on climate prediction. In addition to the maintenance of the Atlas/Triton buoy network in the Pacific, a Japanese initiative to improve observations in the Indian Ocean will help to understand the processes in this region.

ii) Technical and Administrative Issues

To promote monsoon simulation and modeling, further computing resources and infrastructure are required, including sufficient CPU time allocation. Most of the monsoon-affected countries are developing countries, and communication between the WCRP community and scientists/operational agencies in these countries is still lacking, particularly in Asia, though GAME activity has much improved the situation. Mechanisms for connecting major numerical weather prediction centers, the science community, and regional end users need to be improved. The NOAA-climate testbed in the American sector and the DEMETER project in Europe/African sector will function for improving this situation. A similar activity may be strongly recommended in Asia. The APEC climate center being established in Korea may at least partly function to improve the situation in Asia.

What Needs to be Done to Address the Key Issues?

i) High resolution modeling

Through conducting high resolution modeling using CRMs we need to know if high resolution modeling can alleviate key problems (e.g., diurnal cycle, convection over land, MJO etc.).

We also need to simulate the annual cycle without convection parameterization to find out if parameterization is really not the problem. For these sensitivity studies the Earth Simulator (ES) in Japan should further be promoted, including allocation of more CPU time. To solve this issue in the ES, international support may be required for more climate runs on the simulator. This will answer question of whether the way forward is cloud-resolving models.

ii) Need to Foster Research/Application of Seasonal Predictions

We need to promote continuous assessment of predictability with ensemble seasonal predictions: even with a perfect model we don't know the extent of potential predictability. A more extensive repository is needed for monsoon forecasts, particularly for Asian countries. In addition, we need seamless/unified approach to data assimilation (land surface/ocean/atmosphere). The use of separate assimilation systems for land-surface, ocean, and atmosphere is anachronistic. We need to try to get better analyses using coupled data assimilation.

To detect model errors, we need to run climate models at NWP resolution and run in assimilation mode, which then could apply sophisticated 1-time step analysis.

iii) Observations

Data issues need to be improved further. For example, CMAP precipitation data differ largely from those of TRMM in the Maritime Continent. The lack of observations of hydroclimate in the Indian Ocean and the Western Pacific warm pool region need to be rectified, through GEO and GCOS, for example.

GEWEX/CLIVAR Collaboration

We need to enhance coordination and collaboration between GEWEX and CLIVAR through working group and panel activities, including a) to invite GEWEX people to CLIVAR AAMP meetings, b) to coordinate meetings together, and c) to strengthen feedback/interaction of GCSS with GCM/monsoon modeling efforts (e.g., WGCM, WGNE etc.). In terms of prediction, we need to promote a more holistic attitude. For example, empirical schemes and dynamical prediction should be combined at ISV and SC scales. Very-high resolution (4-10 km) regional models need to be developed to simulate monsoon cloud systems and convection. As for regional issues, further observations and modeling may be needed for the Maritime continent.

Issues That Cannot be Addressed at This Stage

Due to lack of computing power we cannot address high-resolution modeling and prediction. Due to lack of adequate deep ocean observations and coupled model fidelity, we cannot address decadal predictability.

Towards better coordination of CLIVAR, GEWEX, and other components of WCRP

We should eliminate the CLIVAR/GEWEX split, particularly for the Asian/Australian monsoon region, and establish a more unified Pan-WCRP approach. The monsoon is not naturally split into land surface and ocean–atmosphere components. We also should coordinate prediction related activities. We must not separate observations from prediction (e.g., TAO/TRITON array in the Indian Ocean is in support of prediction). For progress the overall coordination and collaboration within WCRP, a Pan-WCRP monsoon panel may be needed to report directly to JSC.

Appendix A: Workshop Agenda

1st Pan-WCRP Workshop on the Monsoon Climate Systems: Toward Better Prediction of the Monsoons

Wednesday, June 15, 2005

1. Opening Remarks

8:30AM-9:00AM:	Workshop goals, future program integration. H. Cattle, S. Sorooshian

2) Overview of key modeling issues and observational requirements and opportunities under WCRP

9:00AM-9:30AM:	CLIVAR A/A monsoon panel: B. Wang and R. Kumar Kolli
9:30AM-10:00AM:	GAME (Asian monsoon): F. Kimura
10:00AM-10:20AM:	VAMOS: General Modeling Strategy: Ben Kirtman
10:20AM-10:40AM:	MESA: Modeling issues in the main river basins of the South American region: Pedro Silva Dias and H. Berbery
10:40AM-11:10AM:	BREAK
11:10AM-11:30AM:	NAME: Coordination of NAME Modeling and Field Activities: W. Higgins and the NAME Science Working Group
11:30AM-12:00PM:	CCPP ARM Parameterization Testbed: Integration with CEOP data: G. L. Potter
12:00PM-12:30PM:	CEOP monsoon system study: Bill Lau
12:30PM-2:00PM:	LUNCH

3) Invited Presentations: Overview on the fundamental physics and dynamics of monsoons

a. Dynamics of seasonal cycle and intraseasonal variations

2:00PM-2:30PM:	D. Waliser
2:30PM-3:00PM :	J.-P. Duvel

b. Role of air-sea interaction

3:00PM-3:30PM:	S. Woolnough
3:30PM-4:00PM:	BREAK
4:00PM-4:30PM:	N.-C. Lau

c. Boundary layer and low level jets

4:30PM-5:00PM:	Celeste Saulo

Thursday, June 16, 2005

3) Invited Presentations: Overview on the fundamental physics and dynamics of monsoons (continued)

c. Role of land processes and fluxes

8:30AM-9:00AM:	J. Polcher

e. The role of diurnal cycles of heating and convection

9:00AM-9:30AM:	J. Slingo
9:30AM-10:00AM:	D. Lawrence

f. GCSS-activities and parameterization development for monsoon prediction (including DIME activity)

10:00AM-10:30AM:	Christian Jakob
10:30AM-11:00AM:	BREAK

g. Cloud/precipitation processes and cumulus parameterization for monsoon modeling
11:00AM-11:30AM: D. Randall

h. Regional Modeling of Monsoons
11:30AM-12:00PM: Yuqing Wang

i. Predictability and Prediction of monsoon
12:00PM-12:30PM: P. Webster
12:30PM-2:00PM: LUNCH
2:00PM-2:30PM: T. Palmer

j. VACS/AMMA
2:30PM-3:00PM: A. Giannini, J. Polcher, C. Thorncroft, and K. Cook

4) Modeling and Predictability Efforts
3:00PM-3:30PM: UCLA: C. R. Mechoso
3:30PM-4:00PM: BREAK
4:00PM-4:30PM: NCEP: S. Lord
4:30PM-5:00PM: U. Tokyo: M. Kimoto
5:00PM-5:30PM: Europe: H. Le Treut

Friday, June 11, 2005
5) Working Group Breakout Topics
a. Strategy for parameterization development and observational data requirement for process studies (Chair: J. Polcher)
b. Strategy for system modeling and observational data for large-scale model validation (Chair: Ken Sperber)
c. Monsoon prediction and required monitoring network (Chair: T. Yasunari)
9:00AM-10:30AM: Working Group Discussions
10:30AM-11:00AM: BREAK
11:00AM-12:30PM: Working Group Discussions
12:30AM-2:00PM: LUNCH

6) Plenary session: reports from the working group chairs and discuss/agree on the way forward, including planning and integration for a pan-WCRP monsoon modeling activity (Co-Chairs: Ken Sperber, Tetsuzo Yasunari)
2:00PM-4:00PM: Plenary Session
4:00PM-4:30PM: BREAK
4:30PM-5:30PM: Plenary Session

Appendix B: Workshop Attendees

Annamalai	H.	IPRC/SOEST University of Hawaii 1680 East West Road, POST Bldg 401, Honolulu HI 96822	USA
Arrit	R.	Iowa State University Dept. of Agronomy 3010 Agronomy Hall, Ames, Iowa 50011	USA
Berbery	H.	University of Maryland, 3411 Computer and Space Science, College Park MD 20742-2425	USA
Cattle	H.	IPCO Southampton Oceanography Centre, Empress Dock, Southampton SO14 3ZH	UK
Chang	C.	Dept. of Meteorology Naval Postgraduate School Monterey, CA 93943	USA
Duvel	J.-P.	Laboratoire de Meteorologie Dynamique NS - 24, Rue Lhomond 75231 - Paris Cedex 05	France
Farfan	L.	CICESE, Unidad La Paz Miraflores #334 La Paz, Baja California Sur Mexico, C.P. 23050	Mexico
Giannini	A.	Climate Prediction - IRI PO Box 1000 Palisades NY 10964-8000	USA
Hendon	H.	BMRC Box 1289K Melbourne Vic 3001	Australia
Higgins	W.	NCEP/NWS/NOAA Climate Prediction Center 5200 Auth Road, Rm 605 Camp Springs MD 20746	USA
Hsu	H.-H.	National Taiwan University 61 LN 144 Sec. 4 Keelung Road Taipei 10772	Taiwan
Jakob	C.	BMRC Box 1289K Melbourne Victoria 3001	Australia

Jones	C.	ICESS University of California, Ellison Hall Santa Barbara CA 93106-3060	USA
Kang	I. S.	Seoul National University Dept of Atmospheric Sciences Kwanak-ku, Seoul 151	Korea
Kimoto	M.	Centre for Climate System Research University of Tokyo 4-6-1 Komaba, Meguro-ku Tokyo 153-8505	Japan
Kimura	F.	University of Tsukuba 1-1-1 Tennodai, Tsukuba-shi Ibaraki-ken, 305-8577	Japan
Kirtman	B.	Center for Ocean-Land-Atmosphere Studies 4041 Powder Mill Road Calverton MD 20705-3106	USA
Kitoh	A.	Meteorological Research Institute 101 Nagamine Tsukuba, Ibaraki 305	Japan
Koike	T.	Dept. of Civil Engineering University of Tokyo Bunhyo-ku, Tokyo 113-8656	Japan
Kumar Kolli	R.	Indian Institute of Tropical Meteorology Homi Bhabha Road Pune 411 008	India
Lau	W. K.-M.	NASA/GSFC Code 913 Greenbelt Road Greenbelt MD 20771	USA
Lau	N.-C.	NOAA Geophysical Fluid Dynamics Laboratory Princeton University PO Box 30, Princeton NJ 08542	USA
Laval	K.	Universite de Paris 6 Tour 45-55, 3eme et, Case Postale 99, 4, place Jussieu F 75252 Paris Cedex 05	France
Lawford	R.	International GEWEX Project Office 1010 Wayne Avenue, Suite 450 Silver Spring MD 20910	USA

Lawrence	D.	NCAR/CGD P.O. Box 3000 Boulder, CO 80307	USA
LeTreut	H.	Universite M et P Curie Laboratoire de Meteorologie 4 place Jussieu, F-75231 Paris Cedex 05	France
Leung	R.	Pacific Northwest National Lab P.O. Box 999/K9-24 Richland, WA 99352	USA
Lord	S.	NOAA/NWS/NCEP Room 207 World Weather Building 5200 Auth Road Camp Springs, Maryland 20746-4306	USA
Marengo	J.	CPTEC / INPE Rod. Dutra Km 40 126300-000 Cachoeira Paulista SP	Brazil
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