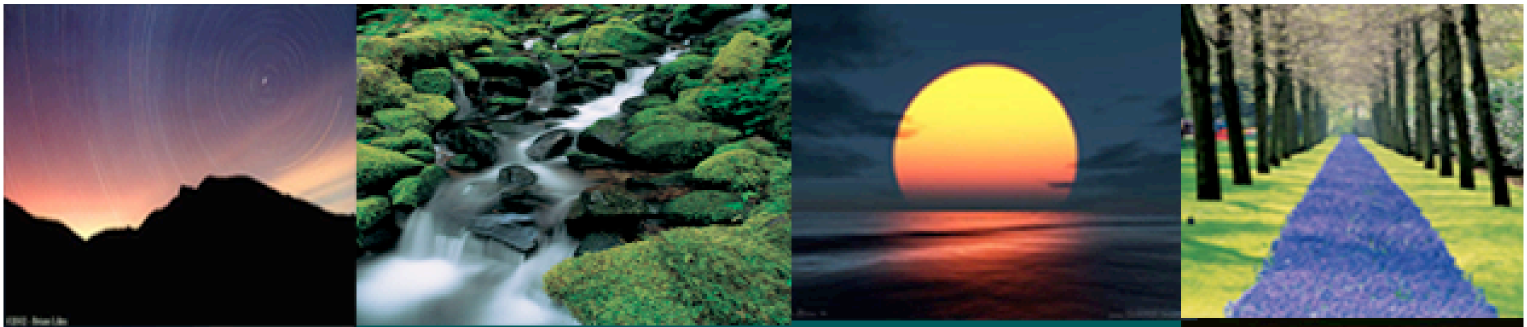

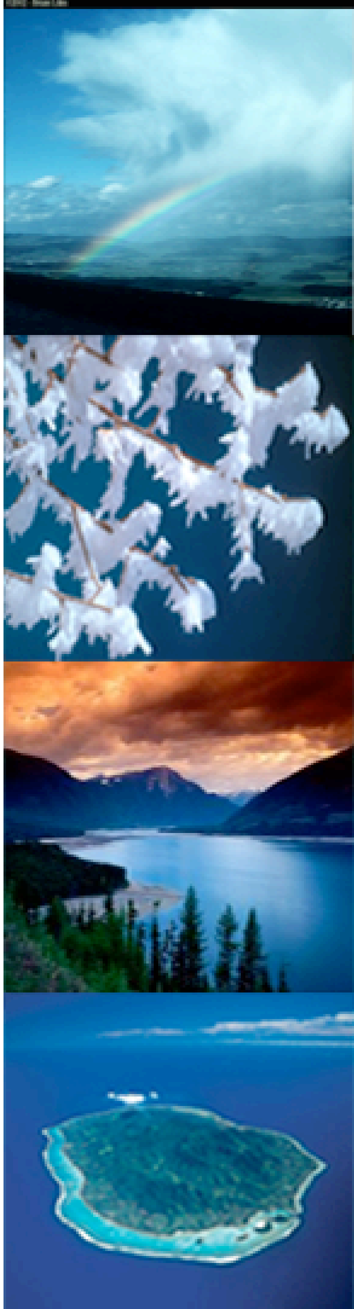

COLA

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2002 - 2006

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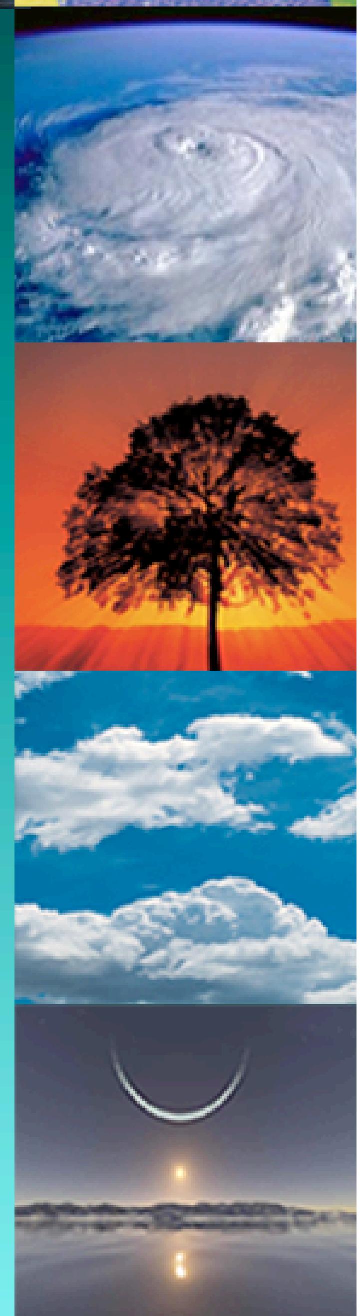

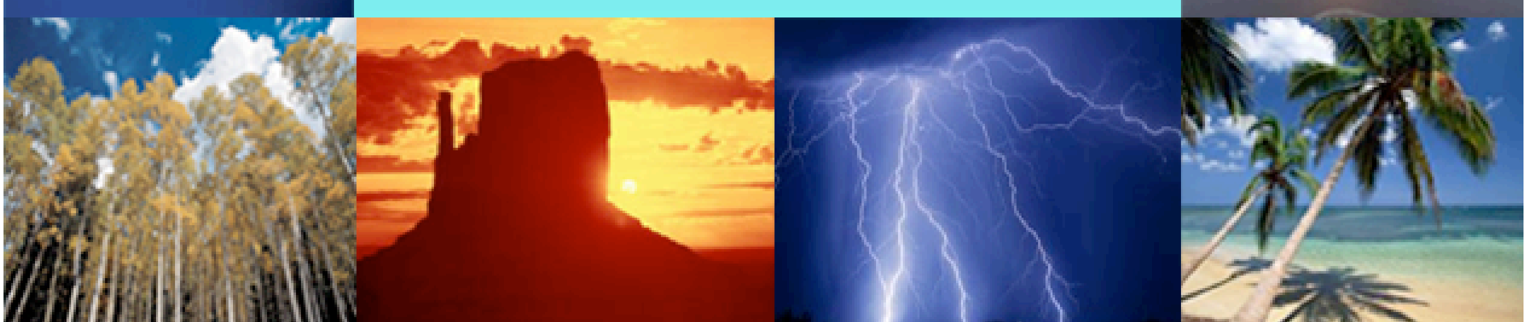

SCIENCE REVIEW
2002 – 2006

Center for Ocean-Land-Atmosphere Studies
4041 Powder Mill Rd., Suite 302
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CENTER FOR OCEAN-LAND-ATMOSPHERE STUDIES
SCIENCE REVIEW - 2002-2006

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PREFACE

The Institute of Global Environment and Society, Inc. (IGES*) seeks to improve understanding and prediction of the variations of the Earth's climate through scientific research in climate variability and predictability, and to share both the results of this research and the tools necessary to conduct this research with society as a whole. Toward this goal, the Institute has established the Center for Ocean-Land-Atmosphere Studies (COLA). With the support of three different federal agencies (NSF, NOAA and NASA), through a single, multi-agency, multi-year research grant, COLA has become a national center of excellence for research on climate variability and predictability. To quote from the 2003 and 2005 COLA Scientific Advisory Committee reports:

> *"The quality of the personnel and the focus of their effort on the seasonal to interannual prediction problem make COLA a preeminent institution that provides national leadership in this area, which is crucial to the nation's effort to provide better climate forecast services."*
>
> *"The work of COLA is of very high quality scientifically, and the omnibus grant allows a focused collaboration that produces a coordinated attack on an important scientific problem that would not be possible without an omnibus grant of this nature."*
>
> *"The remarkable effectiveness of COLA is a consequence of the strong interactions between staff working toward common goals. . This strong "value-added" component depends on the multi-agency form of the funding it receives, the abilities of NASA, NSF, and NOAA program managers to collectively provide such funding, and COLA's modest size and continuity of staff; these are all essential to maintain COLA's capacity to promote its strong staff interactions."*

COLA is widely considered to be a shining example of the successful way that cooperation and coordination among the U.S. federal agencies has led to more flexible and more creative federal support for basic research in climate variability and change. A recent report from the National Academy of Sciences (*Strategic Guidance for the National Science Foundation's support of Atmospheric Sciences*, National Academies Press, 2006) listed COLA as one of four major interagency programs (along with the U.S. Climate Change Science Program, the U.S. Weather Research Program, and the National Space Weather Program) that are supported by the Atmospheric Sciences division of the NSF. We are grateful to our peers in the research community, especially the COLA Scientific Advisory Committee, and the program directors at the federal agencies for approving our proposal and providing crucial guidance over several decades.

J. Shukla
President, IGES

* IGES is a non-profit, tax exempt (501-C-3) institute, incorporated in the State of Maryland.

FOREWORD

The Center for Ocean-Land-Atmosphere Studies (COLA) is a unique environment for research that enables Earth scientists from several sub-disciplines to work closely together on innovative basic and applied research on the seasonal to decadal variability and predictability of Earth's climate. Focused on understanding and quantifying the origins of climate predictability, COLA scientists use a suite of the best available computer models of the Earth's global atmosphere, world oceans and land surface in a mix of theoretical, numerical and practical studies.

The scientists at COLA work with colleagues both within the U.S. and abroad on collaborative projects, and are actively involved in a number of national and international research and planning projects. COLA scientists also serve the broader community in advisory and educational roles. The education of the next generation of atmospheric, oceanic and land surface modelers is critical to the advancement of our science and the improvement of our understanding of the predictability and variability of the Earth's climate. For that reason, COLA has formed a partnership with George Mason University (GMU) to establish a Ph.D. program in Climate Dynamics that was recently reorganized as a full department within the GMU College of Science.

Support for COLA research is provided by the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA), with additional supercomputing resources made available by the National Center for Atmospheric Research and the NASA Center for Computational Sciences. We are grateful to the agencies, the advisory committee members and our many colleagues and collaborators who make this work possible. On a personal note, I am grateful to my friends and colleagues at COLA who gave me the great honor of being selected as Director in 2005. It has been a great pleasure to work with, and to enjoy the trust and confidence of, the excellent COLA scientific, technical and administrative staff.

The scientific and technical activities at COLA are critically reviewed by a Scientific Advisory Committee composed of highly respected leaders in the field. This Science Review summarizes and highlights the research results obtained at COLA during the five-year period of 2002-2006. This report, along with its two predecessors, *COLA Science Review 1993-1996* and *COLA Science Review 1997-2001*, is intended to provide an overview of COLA's scientific and technical accomplishments, obtained with the support of the U.S. federal agencies. A five-year compendium of organizational information about COLA is also included.

Comments about this report are welcome. Please feel free to contact us.

James L. Kinter III
Director

1. INTRODUCTION AND SUMMARY

Research at the Center for Ocean-Land-Atmosphere Studies (COLA) continues to be guided by the scientific hypothesis that there is a predictable signal in the variations of the Earth's current climate which makes it potentially possible to accurately forecast those variations with lead times longer than the inherent limit of deterministic predictability imposed by the chaotic fluctuations of the global atmosphere and the world ocean. Since Shukla (1998) characterized this "predictability in the midst of chaos", COLA scientists have been critically examining this hypothesis in a coupled ocean-atmosphere-land modeling framework that includes both basic research on predictability and applied research on prediction. Building on their experience of over 20 years working together, COLA scientists have established a scientific basis for studying the predictability of climate.

Predictability can be viewed as a theoretical construct, and a property that cannot be separated from the model used to estimate it, as Lorenz first noted in the 1960s. Importantly, COLA scientists take the view that predictability is best examined in concert with real prediction studies, and this duality of predictability and prediction can be used to great advantage. At COLA, we invoke this duality in three ways. First, we use hindcast data sets, created using observed initial conditions, as a primary source for investigating predictability. Second, we use existing operational forecast models in numerical experiments designed to evaluate predictability and sensitivity. Finally, we produce real forecasts with "no cheating" (no information input after the initial time) as a hard test of predictability results.

This line of inquiry has been very fruitful for more than just the past five years. COLA scientists are credited with the demonstration that the atmosphere's lower boundary conditions – sea surface temperature, sea ice, soil wetness, vegetation, and snow – profoundly influence the predictability of climate beyond weather time scales. This was accomplished by means of literally hundreds of atmospheric general circulation model experiments with observed boundary conditions. COLA took the lead in demonstrating that general circulation models of the physical climate system can be used to exploit this predictability for the purpose of making skillful dynamical seasonal predictions. The question of how the land surface influences climate predictability has been a special topic of interest at COLA, dating from the pioneering work of Shukla and Mintz, and the role of land-climate interaction is now understood to be an important determinant of seasonal climate. On longer time scales, the predictability of El Niño and the Southern Oscillation (ENSO) has been thoroughly examined through a number of novel modeling strategies developed by COLA scientists, including the anomaly coupled model and the interactive ensemble. More broadly, COLA has introduced a number of modeling and analysis tools and data sets that are of critical importance not only for advancing our understanding of the theoretical aspects of predictability and the practical aspects of prediction, but also are in use in research and educational settings around the world.

The numerical experiments conducted at COLA are now routinely composed of ensembles of model simulations to provide estimates of uncertainty and to make it possible to express the results in a probabilistic framework. During the period of this report, the work has expanded to multiple state-of-the-art models, supported by the U.S. national laboratories, to provide a more robust estimate of the model dependence of the results and to provide a more direct path from research results to operational climate forecasts and improvement of the national models. The research scope has been extended to include all seasons of the year, all ocean basins, and more quantitative understanding of monsoons and of the global hydrological cycle.

The principal findings of COLA research for 2002-2006 may be summarized as follows.

- The variations of seasonal predictability of climate over time – on interannual, decadal, and longer time scales – and in location on the globe are associated with multi-scale interactions in the atmosphere, interactions between the atmosphere and ocean, and interactions between the atmosphere and land surface. There are preferred locations for coupled interactions between atmosphere and ocean or between land and atmosphere.
- Predictability is enhanced by ocean-atmosphere interactions both locally through intrinsic modes of variability and remotely through teleconnections, and by land-atmosphere interactions in particular areas for particular seasons. The role of noise, both atmospheric and oceanic is fundamental. Long-term climate change may alter these relationships.
- Innovative modeling methods and new mathematical techniques developed at COLA have led to conceptual leaps that have significantly advanced the study and understanding of predictability.
- Better models, whose systematic errors are reduced through better representation of physical (coupling, parameterizations) or dynamical processes (resolution) or through empirical correction, can produce better forecasts not only of the mean climate but also of anomalies.
- Multiple dynamical models can be exploited to form a consensus forecast that is superior to any individual forecast, to provide an estimate of uncertainty, and to be used in dynamical (not just statistical) combinations that further elucidate predictability.

Each of these findings is summarized below.

Characterizing seasonal predictability. It is common experience that weather forecast skill varies from time to time and season to season. The same is true for seasonal climate predictions: long experience in statistical prediction of climate has shown, for example, that the extratropical winter is more predictable than the extratropical summer. Through an exhaustive series of dynamical seasonal prediction (DSP) experiments, applied to all four seasons, to ocean and land surface conditions separately, and to multiple National models, we have shown that

- boreal winter predictability is dominated by the response to ENSO
- boreal summer predictability is more variable and depends more heavily on the antecedent land surface conditions
- there is an asymmetry in predictability between the autumn before and the spring following an El Niño (or La Niña) event.

Year to year variations in predictability are also associated with both interannual and secular changes in the behavior of sub-seasonal regimes. To overcome the limitations of the short record of upper air measurements, we have used large ensembles of model integrations to effectively increase the sampling of regimes, which has led to a more robust estimate of the distribution of circulation patterns and also has revealed a secular trend in some of the patterns of variability.

The importance of scale interactions for seasonal predictability has become increasingly apparent. For example, we found that the forcing by extratropical eddies is an important component of the maintenance of the large-scale atmospheric modes of variability that dominate the boreal winter hemisphere. On the other hand, there are modes of atmospheric variability that operate independently over the mid-latitude ocean basins. Scale interactions are also important in the predictability of ENSO. We have demonstrated that the tropical Pacific is a fundamentally nonlinear system on interannual time scales since the mean state is directly linked to ENSO variance. Teleconnections from the Pacific to other regions are more complicated than simple wave propagation or dispersion. For example, the Atlantic and Indian Oceans both exhibit intrinsic modes of variability that are in some cases modulated by and in other cases triggered by the remote effects of ENSO in the Pacific. In the atmosphere, shifts in the large-scale overturning circulation (Walker cells) and atmospheric Rossby waves along with coupled interactions between the atmosphere and the Indian Ocean strongly influence the variability and predictability of the south Asian monsoon. It should be noted, however, that current state-of-the-art coupled models are still inadequate for simulation or prediction of the monsoons, although regional downscaling can help by improving the representation of topographic effects.

Predictability is enhanced by ocean-atmosphere interactions and land-atmosphere interactions, with high-frequency noise and low-frequency climate change playing important roles. Ocean-atmosphere interaction was put forward as the mechanism for ENSO in the mid-1960s, and this hypothesis has been thoroughly scrutinized for at least the past 25 years. Improving our ability to understand the predictability of the tropical oceans and their interaction with the global atmosphere directly influences our ability to predict the response to slow variations in conditions at the Earth's surface, as originally suggested by Charney and Shukla (1981). A basic question that still cannot be answered with available observations is whether or not ENSO is fundamentally an unstable or a damped coupled mode. The interactive ensemble methodology developed by COLA can directly address this question and provide a quantitative answer, albeit model-dependent. We have also learned how to use a regional coupling approach to separate intrinsic modes of variability from remotely-forced modes.

A similar hypothesis about the role of land surface processes and their interaction with the atmosphere has been under study for nearly as long. In a breakthrough study, called the Global Land-Atmosphere Coupling Experiment (GLACE), COLA scientists, in collaboration with colleagues at several laboratories, have shown that the sensitivity of seasonal climate predictability to variations in the land surface conditions is highly variable, both in location and from year to year, with the most highly sensitive locations in the transition regions between wet and dry climate zones. The GLACE analysis also showed how disparate the various models are in their representation of this sensitivity. Combining the effects of ocean- and land-atmosphere interaction in several case studies, notably the 2002 continental U.S. drought and the 2003 European heat wave, we found that persistent sea surface temperature (SST) anomalies and soil moisture anomalies can independently influence extratropical climate predictability as well as work in tandem to produce extremes. All these studies were made possible by COLA's development of a global soil wetness and land surface flux data set.

Considerable effort at COLA over the past five years has been devoted to studying the important role that atmospheric noise has to play in mediating various processes in the tropics and dominating ocean-atmosphere interactions in the extratropics. Oceanic noise and unstable coupled feedback processes are important in certain regions, such as the western Pacific Ocean. One open question is the role that is played by noise in the land surface conditions. In studies of the impact of secular changes in the background climatic state on predictability, we found that changes in one set of interactions can alter the predictability associated with another, e.g. land surface state changes in the tropics can shift the distribution of ENSO interactions.

Development of innovative methods. COLA scientists have developed new techniques both for innovative experimental design and for new types of data analysis. There are six such developments that were brought to a level of completeness in the 2002-2006 period.

(1) *Interactive ensemble*. The interactive ensemble (IE) method of combining the fluxes from multiple realizations of an atmospheric model, say, with a single realization of the ocean provides a powerful technique for controlling and/or "playing back" noise. This unique method provides a framework for assessing the role of noise, either atmospheric or oceanic, and for estimating predictability in the absence of noise. Using an IE version of a given model can help assess the stability of that model's natural modes of variability, and it shows where and when atmosphere-ocean interaction is and isn't important. Finally, IE provides an intellectual framework in which to understand the effect of model tuning.

(2) *Regional coupling*. While similar strategies with a mix of prescribed time-varying and climatological SST applied in different ocean basins had been employed previously, the idea of permitting <u>full dynamical models</u> of the atmosphere and ocean to interact only in selected regions (typically a given ocean basin) while specifying the SST in other regions was first applied at COLA (Huang et al. 2002). It has been used to overcome coupled model errors or to evaluate the teleconnections to the extratropics from one or another ocean basin's interactive fluctuations. COLA scientists have used regional coupling in novel experimental designs to assess the intrinsic vs. remotely forced variability and predictability, which have led to a rich series of papers on and fuller understanding of climate variability and predictability in the Atlantic and Indian Ocean sectors. This idea has been carried to the larger community and currently drives a major part of the International CLIVAR Climate of the 20th Century project.

(3) *Optimal persistence*. The optimal persistence methodology was originally developed to isolate patterns of variability with long decorrelation times. Serendipitously, it was found that the technique could also reveal trends and discontinuities in multivariate time series. We have extended this method using cyclostationary principal components to concisely summarize the low-frequency variability in distinct seasons. The technique has been fully grounded in statistical theory and is now sufficiently mature for use in pedagogical and broader research applications.

(4) *Information theory*. A series of papers on the application of information theory to problems in predictability has led to systematization of many diverse results. This work includes the development of a major new technique, called predictable component analysis, for optimally decomposing predictability just like principal component analysis decomposes variance. The emerging framework also provides sensible answers to several fundamental questions regarding the use of singular vectors in predictability analysis, including which norm should be used, what is the relation between maximizing error and maximizing signal, whether singular vectors can be generalized to systems that contain both initial conditions error and stochastic forcing, and whether non-normality enhances or degrades predictability. We now have a tool to address the question of predictability at all time scales using a single method.

(5) *Ensemble Empirical Mode Decomposition (EEMD)*. The application of the Hilbert-Huang transform to climate time series holds great promise as new tool for evaluating variability

and separating signal from noise without the constraints of *a priori* time filtering. We have recently shown that EEMD can provide an alternative reference frame for viewing the mean annual cycle and the anomalous departures from climatology. Wider applications of this technique are being continuously developed.

(6) *GrADS/GDS data and figure sharing.* The Grid Analysis and Display System (GrADS) is universally recognized as the tool of choice among weather forecasters and climate modelers to evaluate their data graphically and quantitatively. It now provides a *de facto* standard with which scientists can organize and exchange their data, metadata and figures. The combination of GrADS graphical software linked with the GrADS Data Server (GDS) data management capabilities and a metadata search tool called Greta permit much more rapid exchange of ideas and results both inside and outside COLA, accelerating and improving the productivity of scientists worldwide. GrADS and GDS are now parts of the common cyberinfrastructure that is ubiquitous in our field, but, like all good infrastructure, they are often overlooked due to their simplicity and intuitive design.

Better models can lead to better climate forecasts. As described above, COLA research takes advantage of the duality of predictability and prediction, which has a long pedigree. Since the advent of successful numerical weather prediction in the mid-1950s, it has been shown that improving a model's representation of dynamical or physical processes that are relevant to the evolution of the Earth's atmosphere leads to improved forecasts of the weather. We have built on these notions to show that improving models by including the coupling of atmosphere and ocean or atmosphere and land, by refining the resolution of dynamical processes, and by better tuning the parameterizations of unresolved physical processes, climate forecasts can be demonstrably improved. While this may seem unsurprising given the experience in numerical weather prediction, it has been more a matter of faith for climate prediction. Model errors, both biases that misrepresent the mean state and errors in statistical properties such as the rectified effects of noise, have a direct effect on individual forecast errors. Errors in initial conditions are equally important and sometimes more important than errors in the statistical properties of model error. We have shown that correcting the bias in surface fluxes, either between atmosphere and ocean or between atmosphere and land surface, leads not only to a better simulation of the mean but also a better simulation of the interannual variability. This is true even for state-independent correction terms, and it has implications for data assimilation as well as model development.

In response to a call for action, COLA scientists helped organize a community effort to focus attention on the systematic errors in coupled model simulations of the tropics. After two community meetings, experiments were organized that led to tangible results. In particular, a major reduction in the tropical bias of the Community Climate System Model (CCSM) has recently been effected, with concomitant improvements in ENSO simulation, as a result of re-tuning the parameterization of convection. The results are consistent with our evaluation of the under-representation of noise in the western Pacific in the CCSM.

Improving models not only leads to better forecasts on seasonal to interannual time scales, but has implications for climate change simulation. In an evaluation of Intergovernmental Panel on Climate Change (IPCC) model simulations of the effects of doubled CO_2, we found that models with a better representation of the full PDF of surface air temperature also tend to have higher sensitivity to greenhouse gas concentrations.

Multi-model ensembles. There is a growing recognition that, because coupled models have such egregious errors in simulation of the mean, annual cycle and interannual variability of the climate, and because different models have different errors, it is necessary to ameliorate the errors in the various models. One method that is grounded in long-standing forecasting procedure as well as statistical rigor is averaging over members of an ensemble to form a consensus. Several experiments, notably the European Development of a European Multimodel Ensemble System for Seasonal-to-Interannual Prediction (DEMETER) project, have demonstrated the efficacy of combining multiple models, not just to form a broader consensus but because ensembles drawn from multiple models statistically outperform ensembles of the same size drawn from a single model. COLA has adopted a multi-model approach in its predictability and prediction research, and has taken the lead in applying two U.S. national models – the NCEP Coupled Forecast System (CFS) and the CCSM – as seasonal to interannual predictability research tools. In the case of the CFS, a set of hindcasts was produced by NCEP, which served as an ideal control data set for several experiments. For CCSM, very little prior experience using the model in prediction mode, with real initial conditions, was available. COLA scientists developed a simple method for importing the ocean initial state from independent ocean data assimilation products, and began making forecasts with CCSM. The forecasts were quite comparable to state-of-the-art dynamical coupled model predictions, although the systematic biases in the model were apparent in nearly every individual forecast. The experiments performed at COLA have included applying the interactive ensemble methodology to both the CFS and the CCSM, mixing the surface fluxes from one model with those from another model to take advantage of each model's simulation strengths, and seeking optimal statistical combinations of members of multi-model ensemble forecasts.

Community service. In addition to the research highlights summarized above, COLA has continued and augmented its service activities, exerting a broad impact on the research and education communities.

First and foremost, COLA's partnership with George Mason University (GMU) has resulted in the establishment of a Ph.D. program in Climate Dynamics that is unique in the U.S. This program was recently elevated to a full department in the GMU College of Science, and has already produced a number of graduates who have taken positions in research and education across the country. A full complement of graduate students now routinely enrolls in the program each year.

After more than a decade of development and support, the Grid Analysis and Display System (GrADS) continues to be the tool of choice for analysis and graphical display of large meteorological and oceanographic data sets. The program along with the services of Jennifer Adams of COLA were put to good use in the creation of many of the figures for the second edition of Introduction to Atmospheric Science, by Wallace and Hobbs. Under separate funding, GrADS was combined with the http-based OPeNDAP data transport protocol (formerly called DODS) to build the GrADS Data Server (GDS), which is now in use worldwide at dozens of data repositories to serve geophysical data sets to research and educational users.

Finally, the adoption of two national models – CFS and CCSM – as described above, has had a major impact beyond COLA. The analysis of the CFS systematic error, both its prediction and simulation of ENSO and its simulation of the tropical Atlantic, has led to improved understanding of the model's forecast behavior through the National Weather Service Science and Technology Infusion Program and to potential improvements in the model through the diagnosis of the origin of the systematic error in the Atlantic, which is nearly entirely due to erroneous cloud-radiation interaction and resultant surface heat flux errors. This is also an interesting science result since it is in stark contrast with the primary source of error in the tropical Pacific, namely the misrepresentation of the wind stress. Likewise the adaptation of the CCSM for seasonal to interannual climate prediction provides a linkage between the IPCC-class models, which are used to simulate the response to changing greenhouse gas and aerosol concentrations, and the coupled ocean-atmosphere models that are used in operational climate prediction. Consistent with the World Climate Research Program's new framework, Coordinated Observation and Prediction of the Earth System (COPES), the seamless problem of days-to-decades climate simulation and prediction can begin to be addressed.

In the sections that follow, we provide an overview of scientific and technical accomplishments achieved by COLA scientists during 2002-2005. This material is organized exactly in the same way as the COLA omnibus proposal to facilitate comparison with the proposed work. Section 2 describes work on predictability of seasonal to interannual climate variations, including the DSP work, ENSO, tropical Atlantic and Indian Ocean sectors, and the south Asian and South American monsoons. In section 3, we single out land-atmosphere interactions, primarily because COLA has taken the lead in examining this aspect of climate predictability and also because COLA continues to maintain an active land surface model and data set development enterprise. Our work on how the secular changes in climate may affect predictability on seasonal to interannual time scales is described in section 4, including both tropical land use changes and the effects of a changing background mean state. Section 5 summarizes COLA contributions to the mathematical aspects of predictability in information theory and innovative techniques. Because COLA funding is provided by NSF, NOAA and NASA in a single multi-agency five-year grant, there is an expectation that ideas and innovations will arise that were not necessarily fully formed in the proposal. Section 6 describes selected such ideas. Section 7 provides an organizational overview of COLA contributions to education, the research community, the funding agencies, and information technology. A comprehensive list of peer-reviewed publications, technical reports and invited presentations is provided in section 8.

2. PREDICTABILITY OF SEASONAL TO INTERANNUAL CLIMATE VARIATIONS

2.1 Seasonal Predictability

The seasonal predictability research at the Center for Ocean-Land-Atmosphere Studies (COLA) during the five-year period 2002-2006 has built on the strong foundation of boundary-forced seasonal mean predictability during summer and winter that was laid down in previous work to broaden our understanding of predictability. In particular we have extended our understanding of predictability to the transition seasons, to shorter (intra-seasonal) time scales, and to the role of the interactions with the slowly varying ocean and land states in the development of observed extreme monthly-to-seasonal droughts. We have also examined some fundamental questions in climate variability and predictability. What is the nature of the leading large-scale hemisphere-wide dynamical modes of the atmosphere? What is the fundamental difference between tropical and mid-latitude predictability over the whole span of error evolution? Each of these themes is expanded here.

2.1.1 Global ENSO Impacts During the Transition Seasons

The predictability of the autumn, boreal winter and spring seasons with foreknowledge of SST was studied using ensembles (ensemble size of ten) of seasonal simulations of three atmospheric general circulation models (GCMs): the COLA GCM, the National Aeronautics and Space Administration (NASA) Seasonal-to-Internannual Prediction Project (NSIPP) GCM, and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) GCM for the years of 1982-1999 (Straus et al., 2003). The traditional El Niño minus La Niña composites of seasonal mean tropical precipitation for the ensemble means for the spring season (following the events) was very similar to the well-known wintertime results: large positive anomalies near the dateline that extend eastward to the South American coast. The 200 hPa geopotential height composite signals for spring were generally similar to those in winter, if somewhat weaker. However, in the autumn season (preceding the event) the precipitation ensemble mean response is weaker and shifted off the equator in the eastern Pacific, where equatorial SST is too low to support convection.

The model dependence of the signal (defined as the inter-annual variance of the ensemble mean seasonal means) and the noise (defined as the average intra-ensemble variance of seasonal means about the ensemble mean) in the 200 hPa height field is small, a result holding for all seasons studied. This is in sharp contrast to previous studies.

A signal detection technique that identifies the (seasonal mean) pattern most in common (i.e. with the highest signal-to-noise ratio) within an ensemble over the course of the 18 winters was applied to each set of simulations. The optimal patterns for 200 hPa height for boreal winter and spring are similar, although the spring response over the northern extratropics is weaker. The associated optimal time series have serial correlations with the leading principal component of tropical SST that exceed 0.90 for all the GCMs for winter and spring, thus showing a successful extraction of the signal. For autumn, the time series of the two leading optimal patterns each has a serial correlation of over 0.70 with the corresponding principal component of SST. The autumn 200 hPa height leading optimal pattern (response to eastern Pacific SST) represents a nearly uniform tropical warming, while the second optimal height pattern (response to central Pacific SST) shows a robust wave train in the Southern Hemisphere mid-latitudes.

The central findings of this research involve the asymmetry between the autumn (preceding the ENSO event) and the spring (following the ENSO event), and the relevance and utility of signal-to-noise optimization techniques for isolating the signal.

2.1.2 Boundary Forced Predictability of Intra-Seasonal Mid-Latitude Fluctuations

A series of studies focusing on the important intra-seasonal fluctuations that occur during boreal winter in the Pacific – North America region has been carried out in the framework of circulation regimes. In this approach, recurrent preferred large-scale patterns are identified, and used as a bridge between "climate" (seasonal mean) and "weather" (daily) time scales. Understanding the predictability of the regimes on the basis of boundary forcing (SST) has been one of our primary goals.

In the first study (Straus and Molteni, 2004), a cluster analysis was performed on the daily output of a very large (55-member) ensemble of winter seasonal simulations of the COLA atmospheric GCM for 18 recent winter seasons (1981/82 – 1998/99). The ensemble members for each winter utilize the same prescribed, observed, weekly varying SST. The cluster analysis was applied separately to each of the 18 ensembles, so that each set of 55 realizations (for a given SST evolution) is treated as a separate data set. The analysis includes all fluctuations with time scales longer than 10 days, except for the (ensemble mean) seasonal cycle.

Using a partitioning algorithm on each winter ensemble separately, clusters are found in the 200 hPa height field that are significant (vis-à-vis a suitable Gaussian background), reproducible (in randomly-chosen half-length data sets) and consistent (with clusters obtained from the 200 hPa zonal wind field) for *all* winters *except* the strong El-Niño events of 1982/83, 1986/87, and 1997/98. A strong negative correlation (-0.88) between a measure of the strength of the clustering and the NINO3[1] SST index is found. The fact that this correlation is as strong as the correlation between the seasonal mean response and the same SST index indicates clearly that the ENSO-related SST affects the regime structure of intra-seasonal flow as strongly as it does the mean state.

One cluster found consistently in many winters, consisting of a strong ridge over the Alaskan region with associated trough over central North America, is quite similar to the 'Alaskan pattern' identified from observations as being particularly difficult to predict, which occurs preferentially during La Niña winters. This is termed the Alaskan Ridge regime. A regime that is very similar to the seasonal mean response to cold tropical Pacific SST is seen during several La Niña winters.

Circulation regimes are more uncertain in the (relatively short) observed record than they are in large simulation data sets. The SST-forced predictability of observed regimes was assessed in the context of this uncertainty by Straus et al. (2006). Here the circulation regimes were identified from the NCEP reanalysis for the 18-winter period (1981/82-1998/99) and compared to those from the 54-winter period (1948/49-2001/02), hereafter NCEP18 and NCEP54. The sampling properties of the regimes were estimated from the large (55-member) ensemble simulations described above. Two central questions posed were: (a) Are differences in the regimes between the NCEP18 and NCEP54 data sets within the range of internal (chaotic) variability? (b) Are interannual variations in regime frequencies reproducible as a function of SST anomalies?

[1] The SST anomaly indices for ENSO used in this report are area averages: NINO1+2 (10°S-Equator,90°W-80°W); NINO3 (5°S-5°N,150°W-90°W); NINO4 (5°S-5°N,160°E-150°W); and NINO3.4 (5°S-5°N,170-120°W).

As before, the regimes were identified using a partitioning approach to cluster analysis. From the NCEP54 data set, a set of four clusters (Alaskan Ridge, Arctic Low, Pacific Trough and Arctic High, or AR, AL, PT, AH) were found that are significant (vis-à-vis a multi-normal background), and more reproducible (within randomly chosen half-length samples) than would be expected from a multi-normal process. The frequency of the PT (AH) cluster has increased (decreased) significantly over the past two decades. The PT cluster from NCEP18 more closely resembles the El-Niño forced seasonal mean pattern of recent decades than it does the traditional "PNA" seen from NCEP54 (Fig. 2.1.1).

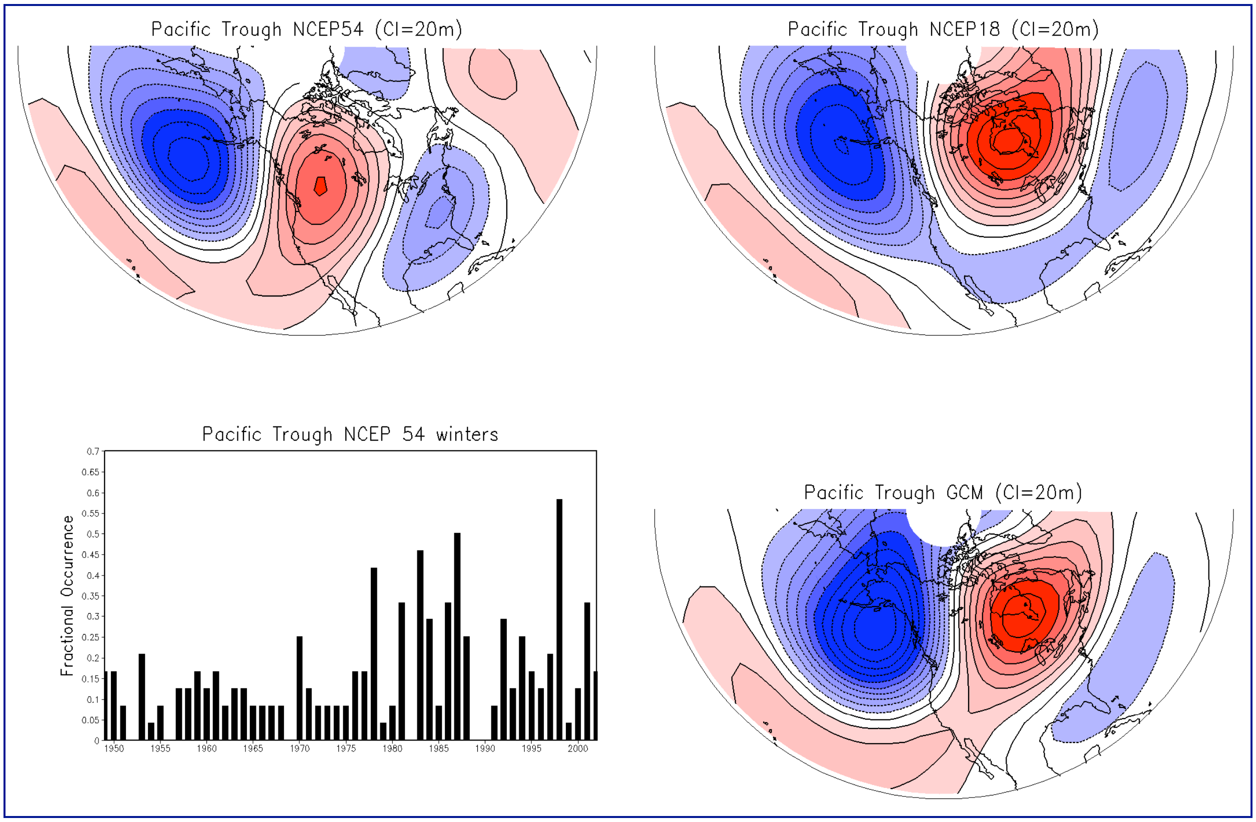

Figure 2.1.1*: The Pacific Trough cluster in wintertime 200 hPa height low frequency flow (time scales more than 10 days), as analyzed by Straus et al. (2006). Upper left: From 54 winters 1948/49-2001/02) of NCEP reanalysis. Upper right: From 18 winters (1981/82-1998/99) of NCEP reanalysis. Lower Right: From 18 winters, ensemble of atmospheric GCM runs (55 members, years matching NCEP18). Lower left: Frequency of occurrence of Pacific Trough cluster from NCEP54 as a function of year. Contour interval is 20 m.*

The GCM simulates the AR, AL and PT clusters (but not the AH). To estimate sampling properties, 55 samples of 18-winter GCM simulations (called EXP18), with each sample containing one simulation per winter, were used to obtain a *pdf* of clusters. In addition, 54-member samples from the GCM simulations (called EXP54) were also constructed, each sample containing 3 (randomly chosen) winter simulations for each of the 18 years. Since any sample of 18 winters in the EXP18 data set has the identical specified time-varying SST as any sample in the EXP54 data set, *pdfs* of pattern correlations between the clusters from the EXP18 and EXP54 sets of samples measure uncertainty due to internal variability. We can then assess whether the differences in cluster properties between the NCEP18 and NCEP54 data sets are in fact due to changes in SST forcing during the two periods. We find that the pattern changes in the PT (and AH) regimes are due to SST forcing changes. The PT change is illustrated in Fig. 2.1.1.

Year-to-year changes in the frequency of occurrence of the PT, AL, and AR clusters in the simulations and in the NCEP18 data set are generally consistent with each other, within the sampling variability defined from the simulations (Fig. 2.1.2). This consistency is an indication of SST-forced predictability. However, the PT (AR) clusters are somewhat under-represented in the simulations during strong El Niño (La Niña) winters, as shown in Fig. 2.1.1. A significant long-term increase (decrease) in the PT (AH) is seen in the NCEP54 data set, as shown in Fig. 2.1.1.

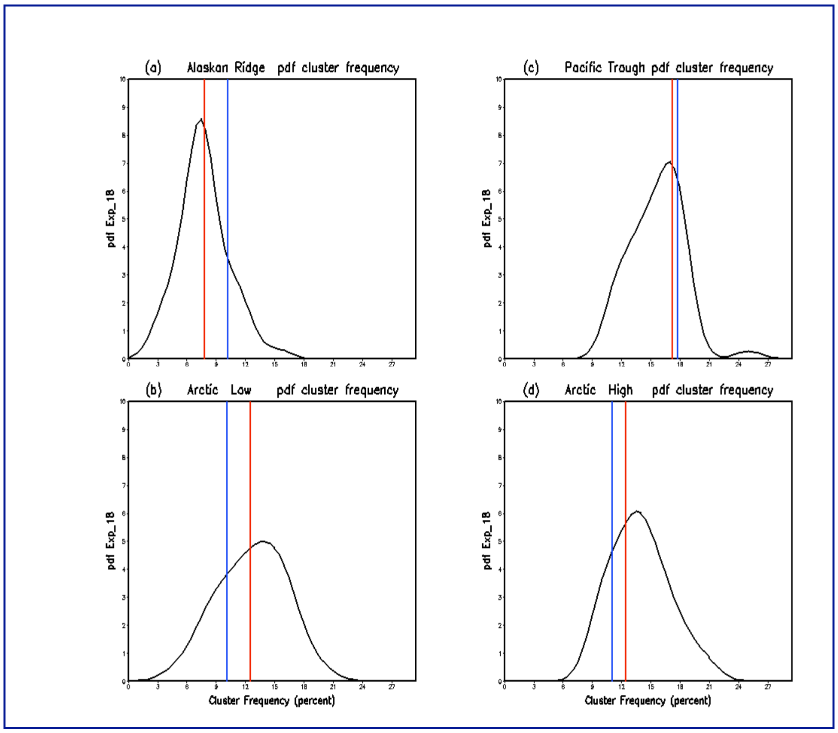

Figure 2.1.2: *Probability density functions (for each of the k=4 clusters) of the cluster frequency (in percent) computed from the clusters of the EXP-18 data set. In all cases, 6 EOFs and a value of α = 0.5 were used. Red (blue) vertical lines show the corresponding cluster frequency from the Grand Ensemble (NCEP18) data sets.*

In order to investigate the relationship between surface weather extremes and the occurrence of a particular regime, Stan and Straus (2006) focused on wintertime blocking in the northern Pacific, which was expected to be related to the occurrence of the Alaskan Ridge regime. Blocking was described by a recently developed blocking index, which is defined in terms of the potential temperature anomaly on a surface of constant potential vorticity, a surface which approximates the tropopause. Using the four-cluster partition described above in the context of NCEP54, it was found that both the frequency of large-scale blocking as well as the number of extended large-scale blocking episodes over the eastern Pacific (western Atlantic) is much higher in the Alaskan Ridge (Arctic High) regime than in other regimes.

The coupling to extreme surface weather, here taken as extremely cold or warm surface temperatures (defined by the extreme 5% tail of the climatological *pdf*) was assessed. For example, up to 50% of the days of extreme cold over northwest North America (northeast Canada) are associated with the Alaskan Ridge (Arctic High) regimes. However, only about 12% of the days in which the circulation resided in the Alaskan Ridge (Arctic High) regimes were associated with extreme cold over northwest North America (northeast Canada). (These results are both statistically significant.)

2.1.3 Origins of the Summer 2002 Continental U.S. Drought

The climatic conditions in the continental United States during spring and summer 2002 were dominated by severe drought across much of the country. In order to determine the origins of the drought, a number of GCM experiments were conducted. Ensembles of 4-month model integrations with the COLA atmospheric GCM were made, initialized at the end of each of the months from February through May 2002, using observed weekly SST as a lower boundary condition. In each ensemble, both climatological and 2002 soil wetness data sets were used to initialize the model soil moisture fields. The results from the first set of ensembles initialized in late February 2002 were discussed in Fennessy et al. (2003). It is worth noting that the equatorial Pacific SST transitioned from weak cold conditions during March 2002 to warm conditions during June 2002.

The first ensemble (labeled "SST") was initialized with climatological soil wetness. The second ensemble (labeled "SST&SW") is identical except it was initialized with soil wetness that has 1 March 2002 soil wetness anomalies derived from the data set of Huang et al. (1996, hereinafter referred to as HDK) imposed on the climatological soil wetness used in the first set of integrations. The HDK soil wetness anomalies were first adjusted for the differences in the monthly soil wetness variability between the HDK data set and the Simplified Simple Biosphere (SSiB) land surface model soil wetness used in the COLA atmospheric GCM. The soil wetness anomalies used to initialize the SST&SW ensemble were similar to those in the original HDK data set, although the magnitude of the negative anomalies across the eastern U.S. are larger than in HDK. After initialization, the soil wetness is predicted by SSiB in both ensembles.

The two ensembles were compared to an 18-year (1982-1999) 180-member March – June (MAMJ) climatology of model integrations which used observed weekly SST and the same climatological initial soil wetness as used in ensemble SST. The anomalously dry soil conditions across much of the U.S. on 1 March 2002 in the initial conditions largely persist throughout the course of the MAMJ integrations.

Large positive (negative) surface air temperature anomalies cover much of the southern two thirds of the US (northern US and southern Canada) in the MAMJ 2002 mean, as in the observed anomaly from the Climate Analysis and Monitoring System (CAMS) data set. The MAMJ mean surface air temperature (and precipitation) anomalies were calculated by subtracting the model climatology from the SST and SST&SW ensembles. The SST ensemble appears to reproduce some of the warm anomaly in the western US, but completely misses the warm anomaly across the southern tier and the cold anomaly to the north. The SST&SW ensemble has a warm anomaly across the southern tier and a weak cold anomaly across southern Canada, and overall looks much more like that observed.

Large negative precipitation anomalies cover much of the central and southern US in the MAMJ 2002 mean, as seen in the observed precipitation anomaly from the CAMS_OPI data set. Both the SST and SST&SW ensembles have negative precipitation anomalies, but those in the SST&SW ensemble are larger in magnitude and extent and bear a closer resemblance to those observed.

Thus, the results suggest that both the evolving SST and the antecedent soil wetness anomalies could help force the 2002 U.S. drought, though the impact of the antecedent soil wetness anomalies appears more significant. While many studies focused on the 2002 drought, this result, emphasizing the large role of the antecedent land surface conditions, is unique.

2.1.4. Climatic Feedbacks During the 2003 European Heat Wave

During the summer of 2003, a record heat wave over Europe occurred, to which the deaths of 35,000-50,000 people in 18 countries were attributed. The Danube River reached its lowest level in more than a century, and Mediterranean SST off the coast of Spain reached the highest levels observed in 45 years (32°C). Temperatures across Europe were above normal for most of the summer, but reached their peak during the first two weeks of August, when most of the deaths occurred.

Ensemble simulations done with a recent version of the COLA atmospheric GCM have been analyzed over the European region. A control ensemble of 10 control simulations were forced by weekly mean observed SST obtained from NCEP. The simulations were initialized in late 1981 and run through the June – September (JJAS) period of 2003. Relative to the 1982-2001 period, the COLA AGCM simulated anomalous warmth over the European region during June, July and August 2003, in response to the observed SST; however the simulated magnitude was smaller than observed.

Figure 2.1.3 shows the ensemble mean simulations of the surface temperature anomaly over Europe for JJAS 2003. The OBS frame show the CAMS JJAS mean surface temperature anomaly relative to the 1982-2001 (20-year) mean. The CNTL frame shows the ensemble mean difference between the JJAS 2003 surface temperature and that from the GCM climatology formed from the ensemble mean for the (20 year) period 1982-2001. The N25N frame shows the difference between a 20-member ensemble initialized from the control runs on 1 June 2003, run forward using the observed (climatological) SST north (south) of 25°N, and the same GCM climatology as above. Frame ISW shows the difference between the 20-member ensemble initialized from the control runs on 1 June 2003 *but with observed soil moisture* and run forward using global observed SST, and the same GCM climatology.

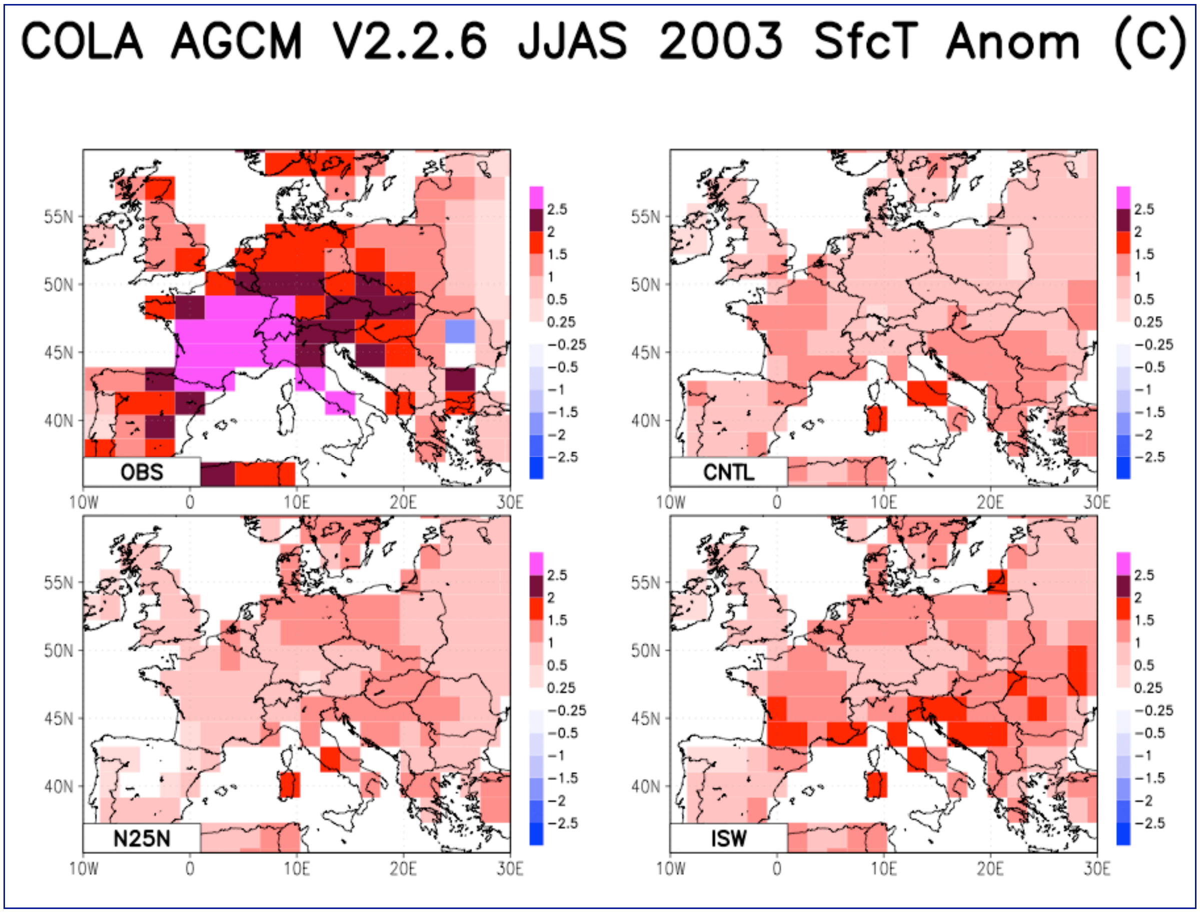

***Figure 2.1.3**: The ensemble mean simulations of the surface temperature anomaly over Europe for JJAS 2003. The OBS frame show the CAMS JJAS mean surface temperature anomaly relative to the 1982-2001 (20-year) mean. The CNTL frame shows the ensemble mean difference between the JJAS 2003 surface temperature and that from the GCM climatology formed from the ensemble mean for the (20 year) period 1982-2001. The N25N frame shows the difference between a 20-member ensemble initialized from the control runs on 1 June 2003, run forward using the observed (climatological) SST north (south) of 25°N, and the same GCM climatology as above. Frame ISW shows the difference between the 20-member ensemble initialized from the control runs on 1 June 2003 but with observed soil moisture and run forward using global observed SST, and the same GCM climatology.*

The CNTL ensemble that included observed SST clearly simulated anomalous warmth during JJAS 2003, although it was much weaker than observed. The N25N simulations reveal that this simulated warmth was due to the SST observed north of 25°N. Additional simulations done by Laura Feudale reveal that much of this warm signal was due to the very anomalously warm Mediterranean and Black Seas (not shown). The ISW ensemble differences reveal that the anomalously dry soil wetness that evolved as a result of the relative dryness of the region during the preceding period (February - June 2003) seems to have further intensified the signal of the heat wave.

2.1.5. Large-Scale Hemisphere-Wide Dynamical Modes

Correctly identifying the fundamental 'modes' of Northern Hemisphere variability of monthly means is of importance for understanding the nature of decadal (and longer) variability in nature, and for validating simulations. In Wu and Straus (2004), a wide variety of techniques were applied to the monthly mean 500 hPa height field from the 54 winter record (1948/49-2001/02) of NCEP reanalysis. A hierarchical cluster algorithm was applied for a variety of EOF truncations. A combination of criteria involving distance in phase space, pattern correlation, well-defined branches of the hierarchical 'family tree,' significance testing, and comparison of the hierarchical clusters to those obtained by the partitioning algorithm and the *pdf* method for clusters, led to a reasonable choice of four or five clusters.

These clusters correspond to the Northern Hemisphere Annual Mode (NAM), also called the Arctic Oscillation (AO), and the Cold-Ocean-Warm-Land (COWL) pattern in both polarities. During the occurrence of NAM-like regimes, the full-field centers of action over the Pacific and Atlantic have positive or negative anomalies simultaneously. For the COWL-like regimes, the center of action over the Pacific is out of phase with that over the Atlantic. Thus the co-existence of NAM-like and COWL-like regimes explains the apparent lack of correlation of monthly mean height fluctuations between the Azores and the North Pacific.

2.1.6. Eddy Forcing Dynamics of Large-Scale Hemisphere-Wide Dynamical Modes

In order to understand how the hemispheric-wide regimes described in section 2.1.5 are forced, Wu and Straus (2003) identified regimes in the zonal mean zonal wind [u] that are closely identified with the regimes, and used the Eliassen-Palm eddy forcing framework to examine the maintenance of these modes.

A cluster analysis was applied to [u] over the domain 20°N-90°N, 1000-30 hPa for the period 1948-2002. The data were obtained from the NCEP/NCAR reanalysis. Four reproducible and robust clusters were found: two regimes represent opposite phases of a pattern of [u] closely associated (via regression) with the Northern Hemisphere Annular Mode (NAM) in 500 hPa height, and two regimes represent the opposite phases of a [u] pattern associated with the Cold Ocean-Warm Land (COWL) pattern in height.

Transformed Eulerian eddy forcing analysis (also called Eliassen-Palm analysis) reveals that the barotropic forcing by the eddy momentum fluxes appears to maintain the wind anomalies in the upper troposphere and balances the Coriolis acceleration associated with the transformed mean meridional circulation. The Coriolis acceleration maintains the wind anomalies against friction in the lower troposphere. This mechanism holds for both NAM-like and COWL-like regimes.

2.2 Interannual Variability and Predictability in the Pacific

COLA's research on interannual climate variability in the Pacific falls into two broad categories – understanding the processes that limit the predictability of ENSO and understanding the underlying physical mechanisms associated with climate variability. Our research strategy relies heavily on numerical experimentation using US national models. However, as is clear from the description below, we also leverage the knowledge gained from several years of research using the COLA coupled model.

2.2.1 Understanding ENSO Predictability

COLA has initiated a major effort to diagnose through analysis and numerical experimentation the predictability of ENSO using the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM3.0) and the CFS. These activities build on the experience gained in using the COLA coupled models (see COLA coupled model ENSO simulation and prediction below). Specifically, our ENSO simulation and predictability work with the COLA coupled model highlights three key research themes that are being explored with CFS and CCSM3.0:

(i) How is ENSO predictability limited by uncertainty in oceanic initial condition?
(ii) How is ENSO predictability limited by unresolved atmospheric uncertainty (i.e., weather noise, Madden-Julian Oscillation or MJO, etc.) as the forecast evolves?
(iii) How is ENSO predictability limited by systematic errors?

Here we highlight results from each of these three research themes.

2.2.1.1 Noise in the Initial Condition vs. Noise as the Forecast Evolves

Stan and Kirtman (2006) have performed a set of identical twin ENSO experiments that are specifically designed to examine how uncertainty in the oceanic initial condition versus uncertainty (or internal atmospheric noise) as the forecast evolves limits ENSO predictability. These experiments were performed with the NOAA CFS model using the operational coupling strategy and the interactive ensemble coupling strategy (Kirtman and Shukla, 2002) developed at COLA. The interactive ensemble coupling strategy is used to control the amplitude of the variability in the air-sea fluxes due internal atmospheric dynamics. With this new coupling strategy we can isolate the relative roles of uncertainty due to internal atmospheric dynamics versus uncertainty in the oceanic initial condition[2].

For example, Fig. 2.2.1 shows the NINO3.4 retrospective forecast root mean squared error and ensemble spread from the control CFS and the interactive ensemble CFS (CFSIE). The solid blue and yellow curves indicate the root mean squared errors based on twenty-four forecast cases (i.e., Jan. 1981, …, Jan. 2004) initialized on January 1st. Each forecast case is a five-member ensemble. The dashed curves correspond to the spread among the ensemble members calculated as a root mean square difference among the members. For comparison, the observed standard deviation multiplied by $\sqrt{2}$ is shown in red. This would correspond to forecast error saturation assuming the model has the correct variance. In a broad sense, the blue curves correspond to ENSO forecasts made with a version of the coupled model with reduced noise due to internal atmospheric dynamics and the yellow curves correspond to the control model.

[2] Additional details of the interactive ensemble coupling strategy and it impact on ENSO: The implementation of the interactive ensemble with CFS involves coupling six realizations of the NCEP Global Forecast System (GFS; atmospheric GCM) to one realization of the GFDL Modular Ocean Model (MOM3). The atmospheric components all experience the same SST produced by MOM3, but the ocean model is forced by the ensemble mean fluxes calculated from the six GFS realizations.

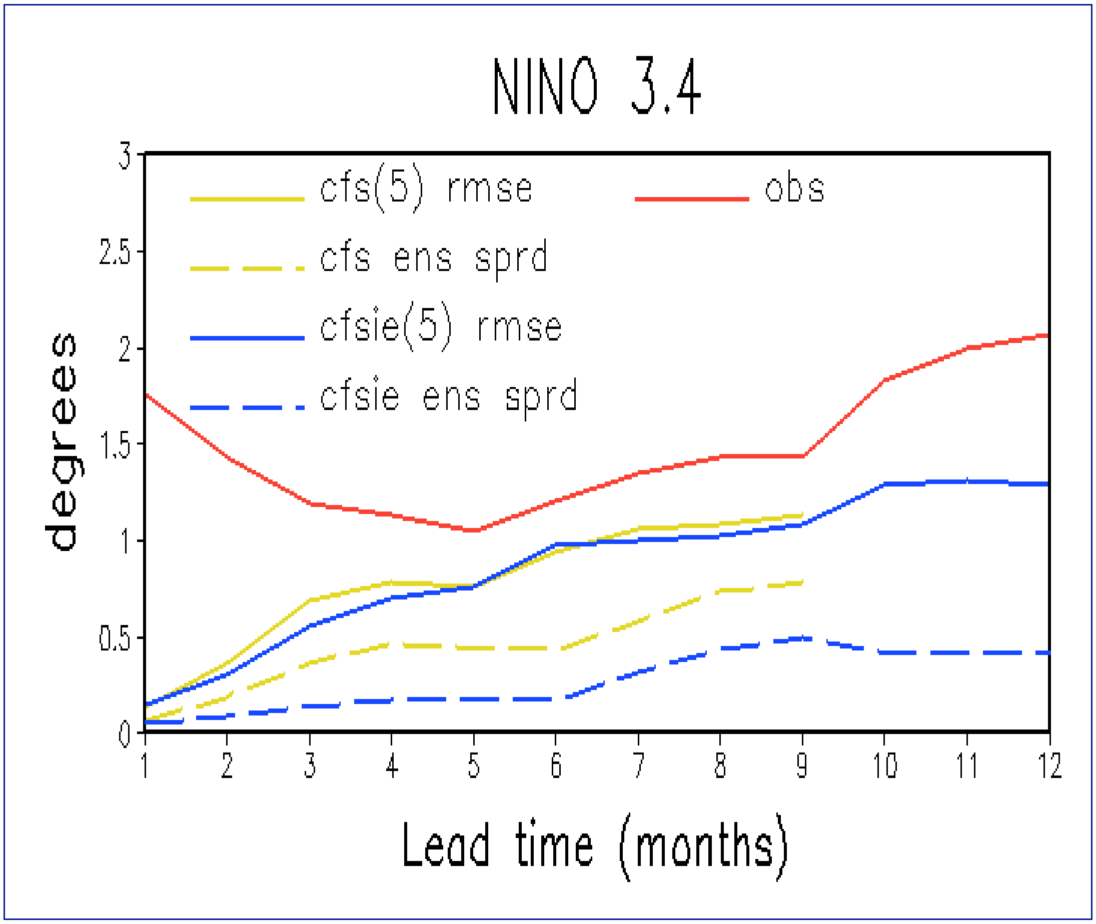

Figure 2.2.1*: NINO3.4 retrospective forecast root mean squared errors from the control CFS (solid yellow) and the interactive ensemble version of CFS (CFSIE; solid blue). The dashed curves correspond for the retrospective forecast spread for the CFS (yellow) and the CFSIE (blue). The red curve corresponds to the observed standard deviation times $2^{1/2}$.*

There are a number of points to highlight. For instance, the noise reduction due to the interactive ensemble has a modest, at best, impact on the forecast errors, but significantly reduces the forecast spread. The forecast error is well below saturation for all 9 months in the case of CFS and all 12 months in the case of CFSIE. Correlation coefficients suggest that the forecasts lose skill (correlation falls below 0.6) for these January cases at around 6 months (not shown). With both the CFS and CFSIE forecasts the spread in considerably smaller than the forecast error. If the forecast system is perfect, then the spread and error should grow at exactly the same rate (i.e., the dashed and solid curves should lie on top of each other). There are two interesting possible interpretations of the relatively small spreads: (i) the forecast systems are overconfident (i.e., the spread is too small and the error is about right), which we can examine by comparing CFS and CFSIE using probabilistic verification techniques; or (ii) the errors in the model or the initial conditions are seriously limiting the prediction skill below what would be expected from the spread (i.e., the error is too large and the spread is about right). The correct answer most likely lies in between these two possibilities; however, the additional analysis described here indicates that we can at least argue that errors in the amplitude of weather noise are relatively unimportant when compared to error in the initial conditions.

In order to highlight some of the points discussed above, Fig. 2.2.2 shows the relative operating characteristics (ROC) curves for the NINO3.4 SST anomaly (see Kirtman 2003 for details of how the ROC is calculated). The ROC curves are one possible skill score metric. The left panel of Fig. 2.2.2 corresponds to the CFS forecasts and the right panel corresponds to the CFSIE forecasts. The closer the circles are to the upper left corner the more skillful the forecast. A forecast system with no skill would lie along the diagonal. According to this metric, both forecast systems are skillful at lead times of five months and both systems indicate that warm events are more predictable than cold events. This last conclusion is opposite to that found with the COLA coupled model (see Kirtman 2003), and is likely due to differences in the systematic error. This is discussed further elsewhere in this science review.

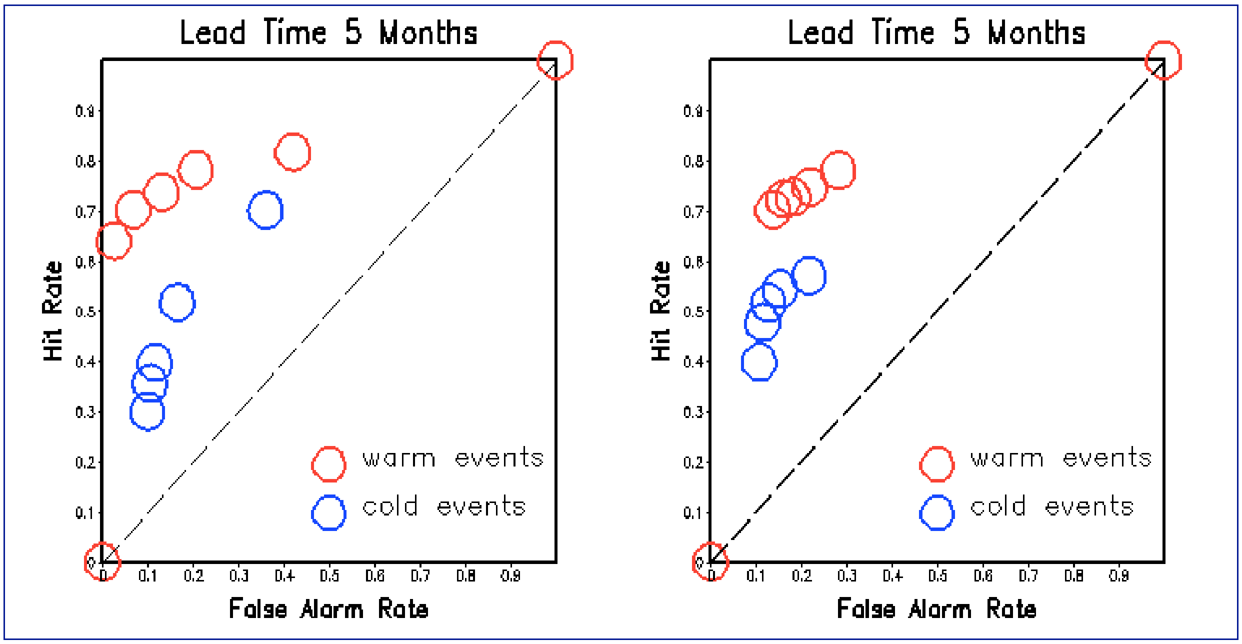

Figure 2.2.2*: Nino3.4 region Relative operating characteristics (ROC) curves for the upper (warm-red) tercile and the lower tercile (cold-blue) for five month lead forecasts. The left panel corresponds to the CFS and the right panel corresponds to CFSIE. The diagonal line indicates zero skill. The closer the circles are to the upper left corner indicates greater skill.*

Similar to the root mean square error, the differences between CFS and CFSIE ROC curves are small. The hit rates tend to be slighter higher for the CFSIE, but the false alarm rates also tend to be higher. The fact that the forecast spread is smaller with CFSIE can be detected in a somewhat smaller spread of the points of the ROC curves. Overall, however, the ROC curves do not indicate that the large reduction in spread is leading to a large reduction in the probabilistic skill. This suggests that the CFS forecasts are not excessively overconfident, and that forecast errors can be reduced by improving the model and the initial conditions.

In terms of idealized predictability, we return to the root mean square error calculation shown in Fig. 2.2.1 except in this case we use one of the ensemble members as the "observations" for verification purposes. The results are shown in Fig. 2.2.3. In both panels the yellow curves correspond to the CFS and the blue curves correspond to the CFSIE. The red curves give the standard deviation of the observation multiplied by $\sqrt{2}$ (i.e., saturation). In this case the observation is assumed to be one the CFSIE ensemble members (reduced noise compared to CFS). The CFSIE curves are identical in both panels as are the curves for the observations. In the top panel, the CFS errors and spread are calculated assuming there is error in the initial conditions, whereas there is no initial error in the CFSIE forecasts. In the bottom panel, the CFS curves are calculated assuming no initial error. In this example, we have chosen to use the CFSIE in place of the observations since it has variance that is in better agreement with observations.

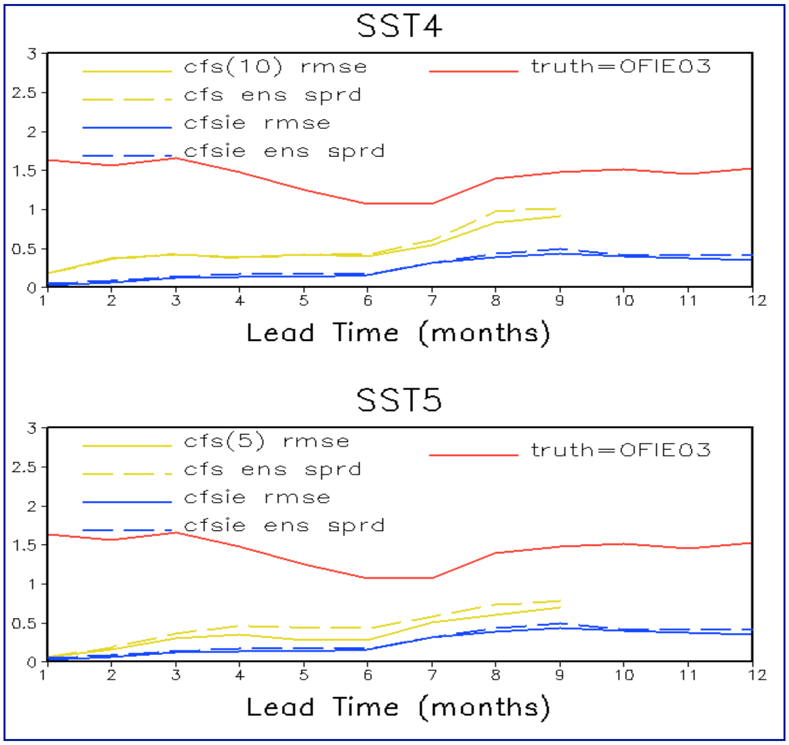

***Figure 2.2.3**: Idealized predictability calculated using root mean square error. In both panels the yellow curves correspond to the CFS and the blue curves correspond to the CFSIE. The red curves give the standard deviation of the "truth" times (i.e., saturation). In this case the truth is assumed to be one the CFSIE ensemble members. The CFSIE curves are identical in both panels as is the observations. In the top panel, the CFS errors and spread are calculated assuming there is error in the initial conditions, whereas there is no initial error in the CFSIE forecasts. In the bottom panel, the CFS curves are calculated assuming no initial error.*

From the top panel of Fig. 2.2.3 we see that both forecast systems are perfect in the sense that the error and spread are coincident. Both forecasts systems are also well below saturation suggesting much more predictability than realized from Fig. 2.2.1. Comparing the yellow and blue curves provides two extremes in terms of predictability. On the one hand, the CFS predictability estimates (yellow curves) represent a worst case in that the model has errors (i.e., larger variance than the observations and more "noisiness") and there are errors in the initial conditions. On the other hand, the CFSIE predictability estimates (blue curves) represent a best case in the sense that they are based on a model that has the correct variance and noise level, and the initialization of the ocean is perfect. The yellow curves in the bottom panel correspond to perfect ocean initialization so that comparing the top and bottom curves indicates how initial errors impact the predictability estimates. Based on these results we conclude that:

(i) The idealized limit of ENSO predictability is considerably longer than suggested by the actual forecast error;
(ii) Excessive noise as the forecast evolves is a significant contributor to the loss of predictability at all lead times; but
(iii) Uncertainty in the ocean initial condition leads to rapid initial error growth that exceeds the growth due to excessive noise in the evolution.

2.2.1.2 CCSM3.0 vs. CFS Predictions: Impact of Model Error

A series of retrospective hindcast experiments with CCSM3.0 are underway at COLA. These experiments are explicitly designed to test an IPCC-class model on the ENSO prediction problem, and, if the forecasts prove skillful, to demonstrate the potential for this system to be part of an operational multi-model suite. Here we briefly present some preliminary results that indicate that the CCSM3.0 has significant levels of skill and that its skill is in some sense orthogonal to CFS (i.e., has information that can be combined with CFS to produce a more skillful forecast). The case studies completed so far also show how CCSM3.0 model errors are imprinted on the forecast evolution.

The difficulty in making forecasts with CCSM3.0 is in initializing the coupled system. In the examples shown here, we have interpolated the ocean analysis produced using MOM3 to the Parallel Ocean Program (POP) ocean component of CCSM3.0. This involved a number of difficult technical issues, particularly with respect to the salinity field. It should also be noted that, in the forecast tests shown here, the atmosphere, land and sea-ice have not been initialized.

Figures 2.2.4-2.2.6 are all in the same format. Each of the panels shows the evolution of the SST anomaly at the equator in the tropical Pacific. The left set of panels corresponds to the CCSM3.0 hindcasts and the right set of panels corresponds to the CFS hindcast. In each set of panels, the upper left corresponds to the observational estimates and the upper right corresponds to the ensemble mean. The remaining six panels show the evolution of each individual ensemble member. Figure 2.2.4 corresponds to forecasts initialized in January 1982, Fig. 2.2.5 corresponds to forecasts initialized in January 1983 and Fig. 2.2.6 corresponds to forecasts initialized in January 1988. The climatology that is used to define the anomalies is based on a total of eight January forecast cases. Although we have not completed enough cases for quantitative skill estimates these results provide a basis for some optimism. Qualitatively, CCSM3.0 has comparable skill to CFS and it apparently has skill in a different direction than CFS. For example, the CCSM3.0 forecasts for cold conditions are significantly more robust than with CFS.

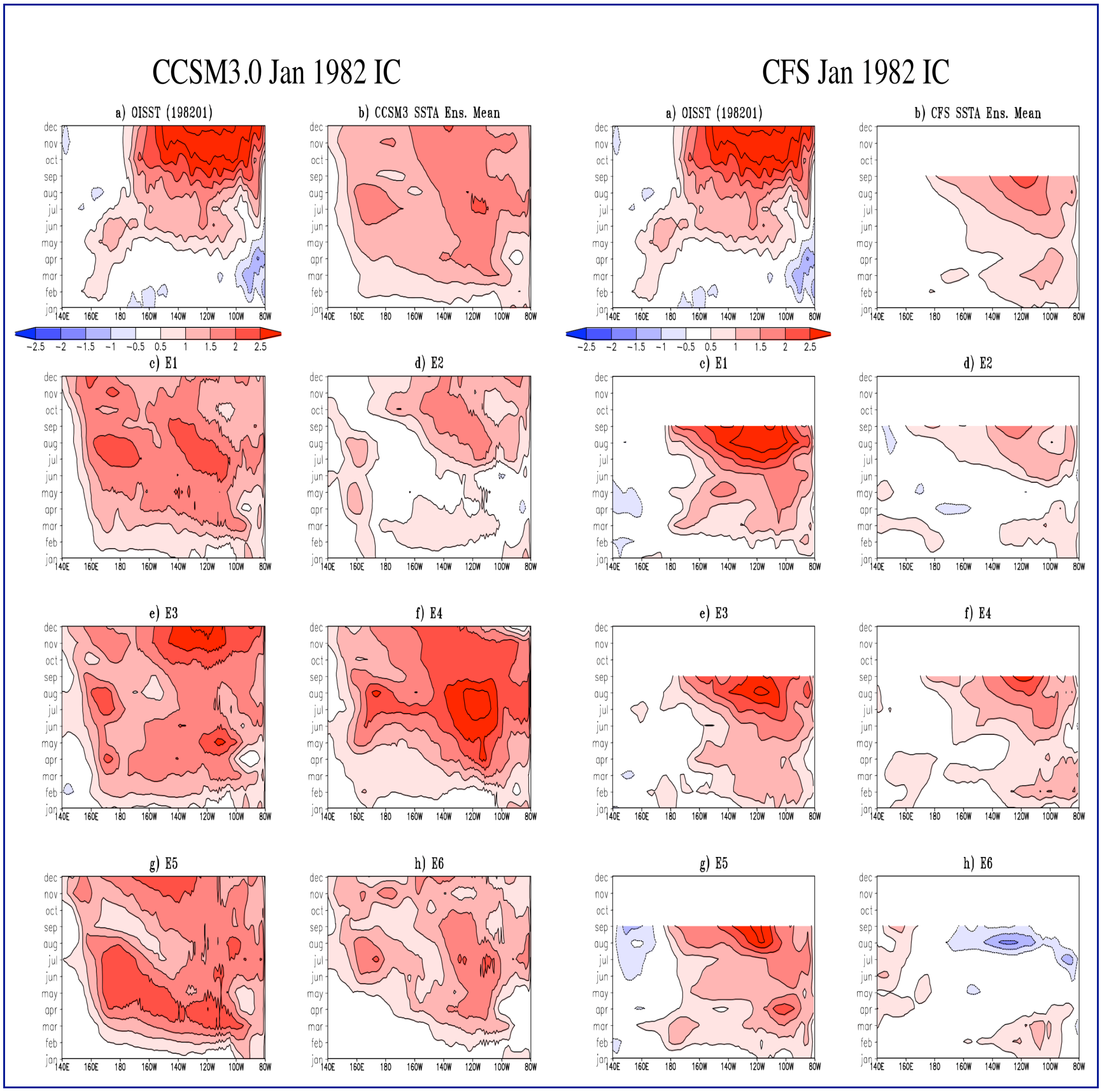

***Figure 2.2.4**: All of the panels show the evolution of the SSTA at the equator in the tropical Pacific. The left set of panels corresponds to the CCSM3.0 hindcasts and the right set of panels corresponds to the CFS hindcast. In each set of panels, the upper left corresponds to the observational estimates and the upper corresponds to the ensemble mean.*

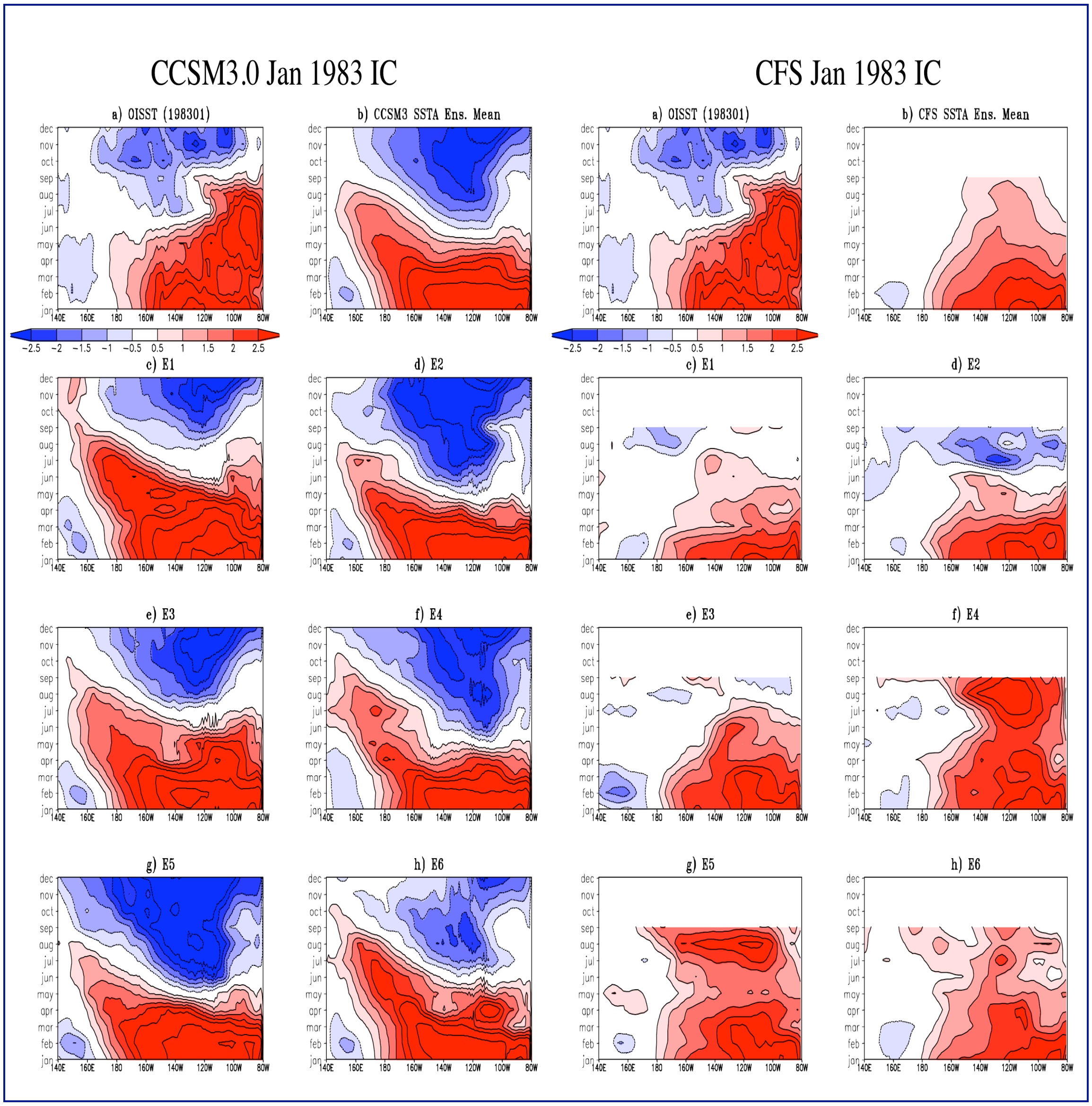

Figure 2.2.5*: All of the panels show the evolution of the SSTA at the equator in the tropical Pacific. The left set of panels corresponds to the CCSM3.0 hindcasts and the right set of panels corresponds to the CFS hindcast. In each set of panels, the upper left corresponds to the observational estimates and the upper corresponds to the ensemble mean.*

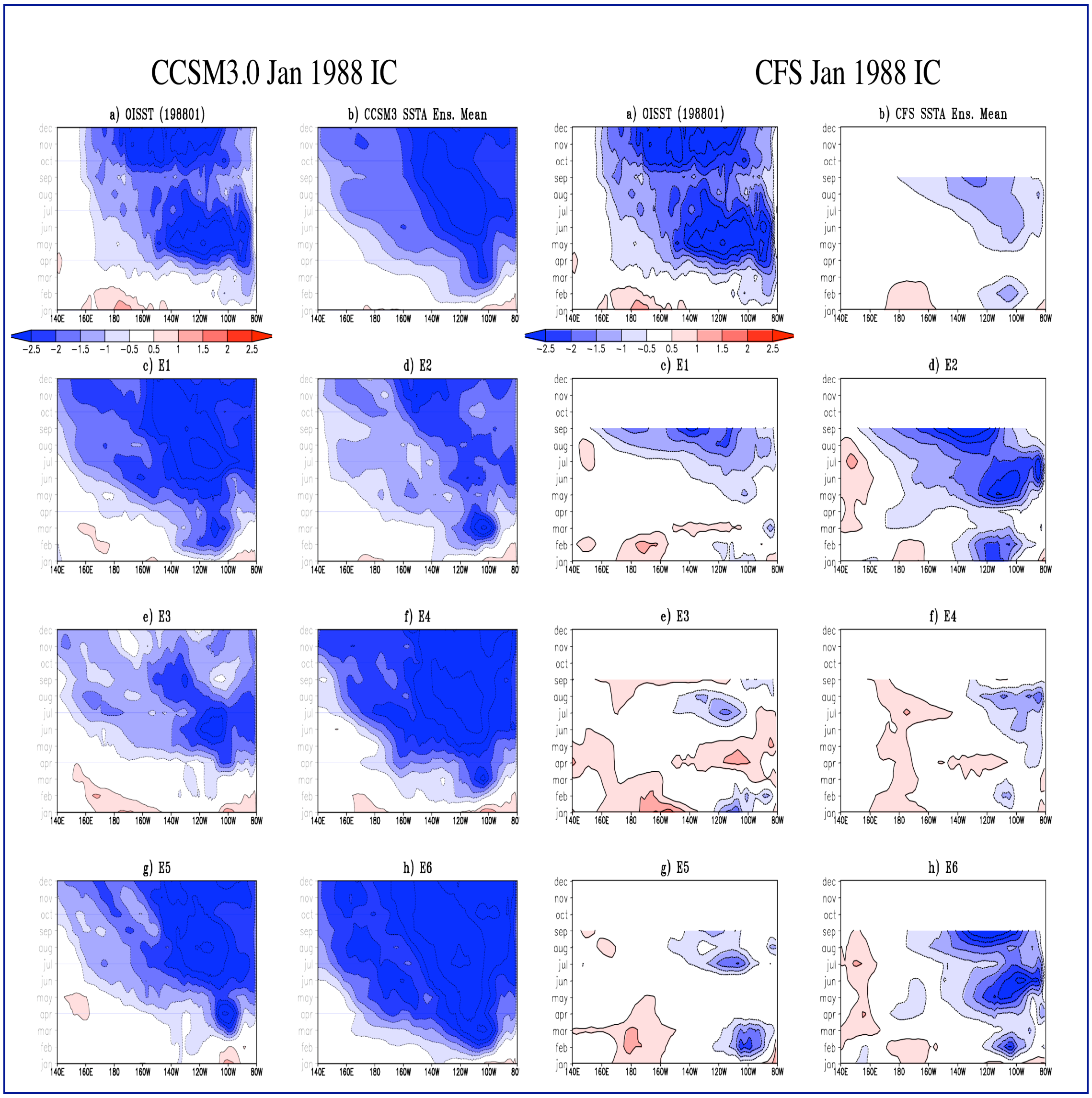

__Figure 2.2.6__: All of the panels show the evolution of the SSTA at the equator in the tropical Pacific. The left set of panels corresponds to the CCSM3.0 hindcasts and the right set of panels corresponds to the CFS hindcast. In each set of panels, the upper left corresponds to the observational estimates and the upper corresponds to the ensemble mean.

These results also highlight some notable errors in both forecast systems that are consistent with their respective long simulations. For example, it is well known that the CCSM3.0 produces ENSO events that extend too far into the western Pacific. This error is easily detected in the forecast evolution shown. Although not shown here, CFS is known to have ENSO events that persist for too long in free simulation mode. This problem can also be detected in the forecast evolution. It is also apparent from the results presented here that both forecast systems tend to initiate a given ENSO event too early in the calendar year. This is likely due to the so-called initialization shock problem.

2.2.1.3 COLA Coupled Model ENSO Simulation and Prediction

Kirtman et al. (2002) described the COLA anomaly coupled general circulation model (ACGCM; Kirtman et al., 1997) and the coupled general circulation model (CGCM, Schneider et al., 1999). The ocean and atmosphere component models for both the anomaly coupled ACGCM and the CGCM are identical - the only difference is in the coupling strategy. This provides the opportunity to make a consistent comparison between the two coupling strategies and examine how relatively large differences in the mean state impact the interannual variability. The emphasis was on the natural variability of the models, particularly in the tropical Pacific. Both models simulate robust interannual variability in the tropical Pacific. The ENSO events in the coupled model have a distinct eastward migration, and during the peak phase of the events, the SST anomalies are trapped in the eastern Pacific. Conversely, the anomaly coupled model ENSO events are dominated by a standing mode, and during their peak phase there is a tendency for the anomaly to extend too far to the west. Both models seriously underestimate the meridional extent of the SST anomaly.

Kirtman (2003) developed a global coupled prediction system that uses a state-of-the-art coupled model and ocean data assimilation system to test the utility of ensemble probabilistic seasonal-to-interannual prediction. The probabilistic forecasts of SST and rainfall were shown to have skill at lead times of up to 7-9 months, and, subsequently, a cost-loss model has been applied to the forecasts to demonstrate their potential economic value (Kirtman and Kinter, 2002). Schneider et al. (2003) reported on a multi-model and multi-institutional collaboration to examine the sensitivity of retrospective coupled GCM forecasts to three different atmospheric GCMs. A series of 40 hindcasts were made with all three coupled models and the results were compared in detail. While the hindcast skill of these coupled models was somewhat disappointing, the overall project has been a success in terms of establishing a multi-model framework for prediction research, providing a baseline measure for future model improvements, and, most importantly, defining strategies for coupled model improvements and coupled initialization strategies.

Misra et al. (2006) compared an ensemble of seasonal hindcasts with a multi-decadal integration from the same global coupled climate model (COLA V3.2) over the tropical Pacific Ocean. They found that the annual mean state of the SST and its variability are different over the tropical Pacific Ocean in the two operating modes of the model. These differences are a manifestation of an inherent difference in the physics of coupled air-sea interactions and upper ocean variability. They argued that, in the presence of large coupled model errors and without using coupled data assimilation, the competing and at times additive influence of the initialization and model errors can change the behavior of the air-sea interaction physics and upper-ocean dynamics.

2.2.1.4 Validating ENSO in Coupled Climate Models

The fidelity of ENSO simulation in a coupled model has been of great interest, both because such models are used on real-time ENSO prediction and because the degree to which they can reproduce the observed features of ENSO is a potentially important metric for models used to project future climate changes. In Misra et al. (2006) we isolated 12 salient features of ENSO that comprehensively characterize both the atmosphere and the oceanic components of the ENSO variability. These 12 features were analyzed in two versions of the COLA coupled model. These features include the mean state of the upper ocean and the overlying atmosphere in the tropical Pacific, the mean annual cycle of the equatorial Pacific SST and wind stress, temporal variability of the NINO3 SST anomaly index, the seasonal phase locking of ENSO, the duration of ENSO events, the evolution of SST anomalies in the equatorial Pacific, the relationship of the NINO3 SST anomalies with the global tropical oceans, the relationship of NINO3 SST and tropical Pacific wind stress, the relationship between NINO3 SST and precipitation, and the mid-latitude atmospheric response to ENSO. A revealing aspect of this comparison study was that there is huge difference in the ENSO simulations between the older and newer versions of the COLA model. Some of these differences, especially in the wind stress anomalies between the two coupled climate models can be related to the vertical distribution of the diabatic heating in the tropical Pacific following the arguments made in Nigam et al. (2000).

2.2.2 Understanding Mechanisms for Pacific Climate Variability

COLA's research on the mechanisms for Pacific climate variability focuses how different processes interact to produces and modify this variability. For example, there are several papers exploiting the interactive ensemble coupling strategy to examine how internal dynamics of both the atmosphere and the ocean impact interannaul climate variability. Scientists at COLA have conducted a number of novel numerical experiments that examine how variability in the "other basins" impact ENSO variability. COLA also continues to lead the field in understanding and diagnosing Indian monsoon variability, and, in particular how this variability interacts with ENSO variability. Finally, COLA has implemented numerical experiments to understand how model systematic errors influence the simulated climate variability.

2.2.2.1 Internal Oceanic and Atmospheric Dynamics and Climate Variability

A set of multi-century coupled general circulation model experiments was designed and carried out. These experiments employed a novel coupling strategy called "interactive ensembles," which was specifically designed to examine how stochastic forcing due to internal atmospheric dynamics impacts climate variability on time scales from seasons to decades. The interactive ensemble strategy is to couple multiple realizations of a particular atmospheric GCM (AGCM) to a single oceanic GCM (OGCM). Ensemble averaging is applied to the air-sea fluxes of heat, momentum and freshwater thereby significantly reducing the "noise" in the fluxes applied to the ocean component without affecting the atmospheric internal dynamic fluctuations that are unrelated to the SST anomaly. Atmospheric noise is part of the real climate system, and we are not arguing that removing the noise is an appropriate mechanism for directly improving the simulation. We are, however, advocating a unique experimental strategy for determining how noise impacts climate variability.

Kirtman and Shukla (2002), in a "proof of concept" paper, compared multi-century simulations from a six-member version of the interactive ensemble with a control simulation (Kirtman et al., 2002) using one realization of the atmospheric model coupled to the ocean component. Their analysis suggested that: (i) the noise reduction only slightly decreases the amplitude of the ENSO oscillation, shortens the periodicity and increases the regularity, and (ii) the global ENSO SST teleconnections and ENSO-monsoon interactions are highly sensitive to the amplitude of the stochastic forcing. Below we highlight how the interactive ensemble approach has been used to understand climate variability in the Indo-Pacific region on interannual to decadal time scales.

The current literature and much of our prior research has focused on the role of atmospheric noise. The role of noise due to internal ocean dynamics has received little attention. The need to include ocean noise was motivated by the surprising results of Wu et al. (2004), who argued that a significant fraction of North Atlantic SST variability was due to internal ocean dynamics. Kirtman et al. (2005) presented a simple linear one-dimensional coupled model that has damped feedbacks and prescribed white noise in both *the ocean and the atmosphere.* They compared the variance produced with and without applying the interactive ensemble coupling strategy. The results are shown in Fig. 2.2.7 (taken from Kirtman et al. 2005), where the ratio of total ocean variance (interactive ensemble divided by the control) is plotted for three different values of the coupling strength and as a function of the ratio of atmosphere noise variance (σ_N^2) divided by ocean noise variance (σ_P^2). The curves plotted in Fig. 2.2.7 correspond to assuming six ensemble members for the interactive ensemble to be consistent with the coupled model results shown below. For weak coupling, the variance ratio becomes relatively large for relatively small values of ocean noise. If the coupling is weak, then the ocean noise has a large effect on the variance. As the coupling strength increases, the variance ratio approaches 1.0 only with considerably larger values of the oceanic noise. In this case, the coupling is more important and the ocean noise has a smaller impact.

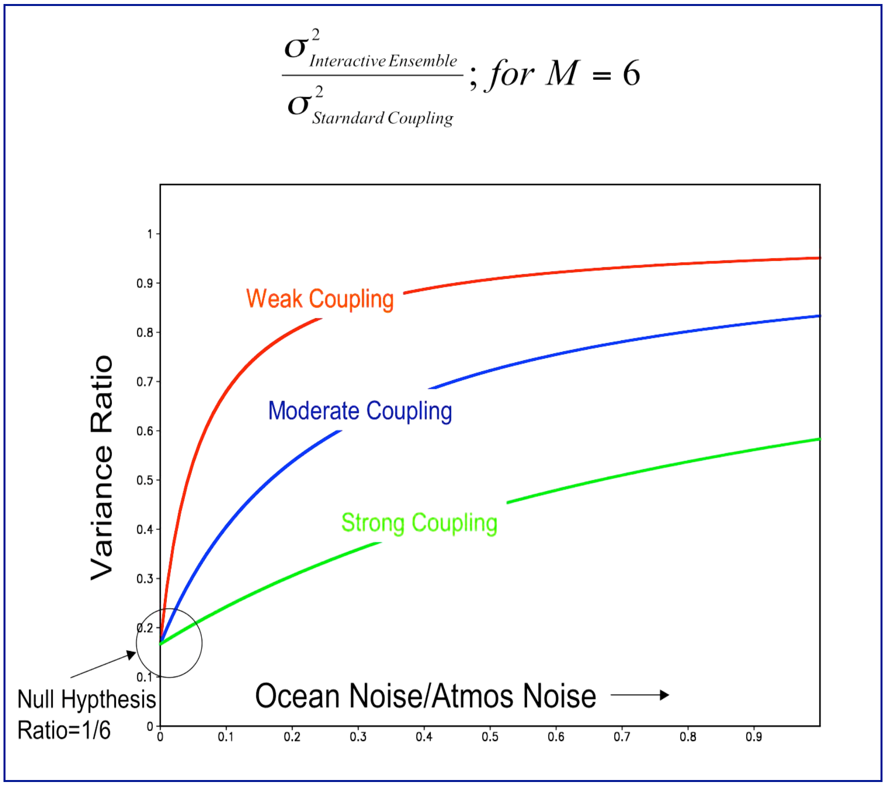

***Figure 2.2.7**: Heuristic coupled model SSTA variance ratio (interactive ensemble divided by standard coupling). The y axis indicates the variance ratio and the x axis indicates the ratio of ocean noise variance divided by atmosphere noise variance. The red curve corresponds to weak coupling, the blue curve indicates moderate coupling and the green curve is for strong coupling.*

In order to interpret the CGCM results presented in Fig. 2.2.8 below, it is useful to consider three ranges of values for the ratio of the variances. (i) If the ratio is on the order of 1/6[3], we conclude that the null hypothesis is likely to be correct (i.e., a stochastically forced system with stable coupled feedbacks) and *the ocean noise is relatively small.* (ii) If the variance ratio is between 0.5 and 1.0 then either the null hypothesis is correct and the ocean noise is playing a significant role or the null hypothesis is incorrect and there are unstable coupled feedbacks or important non-linearities. In other words, we can draw no definitive conclusion, so we need additional experiments to isolate the role of the ocean noise. (iii) If, on the other hand, the ratio exceeds 1.0, then we conclude that there are unstable coupled feedbacks and/or important non-linearities.

[3] The value of six is chosen here since comparisons are made against the GCM implementation of the interactive ensemble using six AGCM realizations.

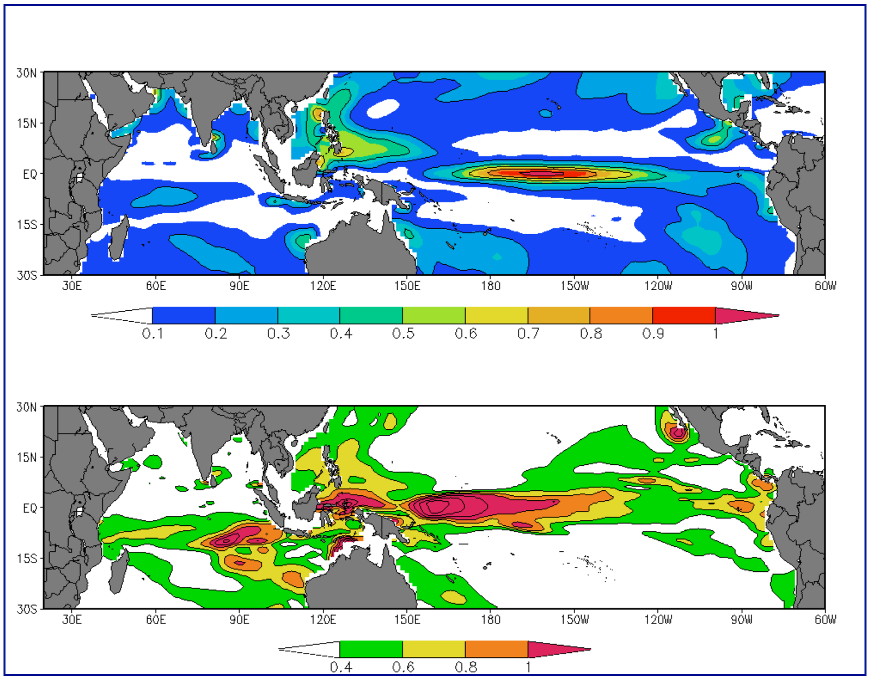

Figure 2.2.8: *(top) SSTA variance based on 100 yr of data for the control CGCM. The contour interval is 0.2°C2. (bottom) The SSTA variance ratio for the interactive ensemble CGCM divided by the control CGCM. The contour interval is 0.2.*

The Indo-Pacific SST anomaly variance from the control CGCM run is shown in Fig. 2.2.8, top, and the variance ratio of the CGCM interactive ensemble to the control is shown in Fig. 2.2.8, bottom. Using the one-dimensional model results shown in Fig. 2.2.7 as a guide, we conclude that there are substantial regions in the western and central tropical Pacific and the eastern south tropical Indian Ocean where there are unstable coupled feedbacks and non-linearity. In the un-shaded regions, there may be some contribution due to the internal ocean dynamics, but the coupled feedbacks are likely to be unimportant. Figure 2.2.8b also shows that there are surprisingly large regions, particularly in the eastern Pacific, where we cannot eliminate noise due to *internal ocean dynamics* as a contributor to the SST variability. Despite the fact that the ocean model is not eddy resolving, it does produce noise due to internal ocean dynamics (i.e., transients), although the statistics are likely to have significant errors. One possible explanation for the results in the eastern Pacific is that tropical ocean instability waves, albeit poorly represented, are making a significant contribution to the SST anomaly variability.

2.2.2.2 Extending the Interactive Ensemble to the Ocean Component

Based on the potential importance of ocean internal dynamics noise identified in Kirtman et al. (2005) and Wu et al. (2004), Kirtman et al., (2006) extend the interactive ensemble approach into the ocean component, thereby reducing the atmospheric interaction with the SST anomaly variability due to internal ocean dynamics. Four separate coupled simulations were examined here: (i) the control simulation consists of one atmosphere coupled to one ocean; (ii) the atmospheric interactive ensemble consists of six atmospheric realizations coupled to one ocean model; (iii) the oceanic interactive ensemble consists of one atmosphere coupled to six ocean realizations; and (iv) the atmospheric and oceanic interactive ensemble consists of six atmospheric realizations coupled to six ocean realizations. An examination of a 300-yr simulation of the atmospheric and oceanic interactive ensemble (iv) indicates that, despite the noise reduction at the air-sea interface, the model produced irregular ENSO events with realistic amplitude, but with a frequency that is too high. This result is consistent with

Kirtman et al. (2005) who argue that the ENSO in this model is a self-sustained oscillation as opposed to a damped system.

Kirtman et al. (2006) compared the ensemble mean SST anomaly variance in the atmosphere and oceanic interactive ensemble to the control model and the atmospheric interactive ensemble, and they found large reductions in variance in the eastern equatorial Pacific and the equatorial Atlantic (i.e., Fig. 2.2.9). In the equatorial Indian Ocean and central western Pacific, the SST anomaly variability was quite sensitive to the atmospheric noise reduction, but relatively insensitive to the ocean noise reduction. The central and western equatorial Pacific region is particularly interesting since it is a region where the ensemble mean SST anomaly variance is substantially larger than the control simulation. This is also the region where almost all coupled models produce excessive ENSO variability. The CGCMs have ENSO events that extend too far to the west. Conventional wisdom has been that this problem is due to error in the mean state. The results shown here suggest that incorrect noise statistics may also contribute to the problem. Numerical experiments to investigate this problem are currently underway.

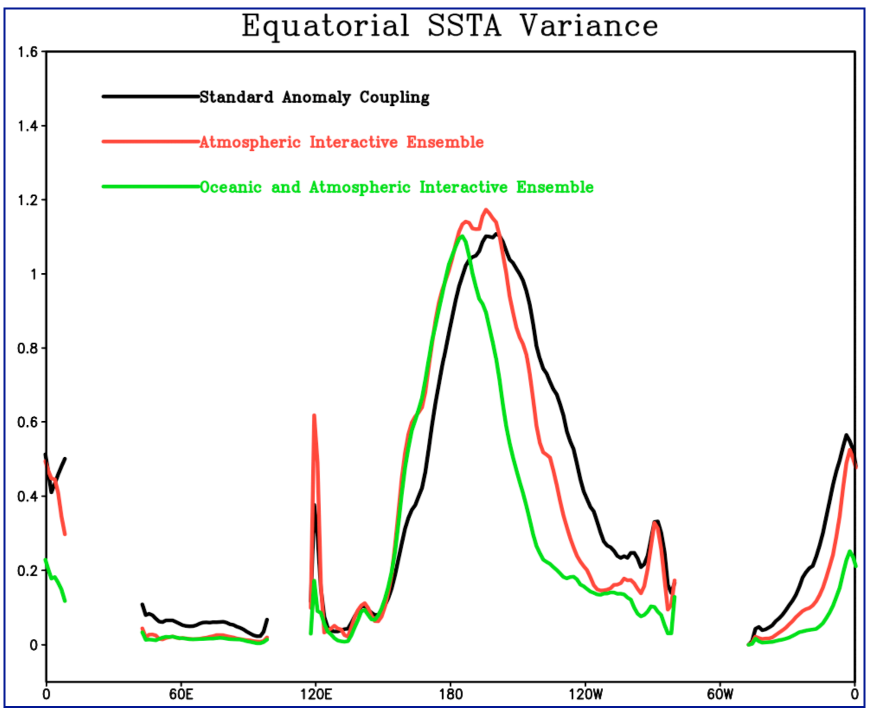

Figure 2.2.9: *Equatorial SSTA variance for the control (black), the atmospheric interactive ensemble (red) and then ensemble mean SSTA variance (green) for the atmospheric and oceanic interactive ensemble.*

We also examined two different variance ratios. The first variance ratio indicates the impact of internal ocean dynamics on SST anomaly variability assuming that this SST anomaly variability is not coupled to the atmosphere. There is a subtlety we want to emphasize, namely that we only are assuming that the SST anomaly variability due to internal dynamics is not coupled. The SST anomaly in general, is coupled; indeed this is the advantage of the interactive ensemble approach. This first variance ratio suggests that ocean dynamics play a substantial role in the SST anomaly variability in the eastern equatorial Pacific, much of the North Atlantic and tropical Atlantic and, most notably the Southern Ocean. In addition, the amplitude of the atmospheric noise at the air-sea interface has implications for the importance of the internal ocean dynamics. The relative amplitude of SST anomaly variability due to internal ocean dynamics increases with decreasing atmospheric noise at the air-sea interface.

The second variance ratio was specifically intended to diagnose how internal ocean dynamics impacts the SST anomaly under the condition that the atmosphere can "feel" this variability (i.e., the internal dynamics is coupled to the atmosphere). Interestingly, this particular variance ratio gives an indication of where atmosphere-ocean interactions enhance or damp SST anomaly variability due to internal ocean dynamics. Based on the model used here, we find that coupling is largely a damping term in the Southern Ocean and the North Atlantic. In the tropical Indian and Pacific Ocean there are significant regions where the coupling enhances the SST anomaly variability due to internal ocean dynamics. Some enhancement is also noted in the tropical Atlantic. The detailed regions of enhancement are sensitive to the amplitude of the atmospheric noise at the air-sea interface.

2.2.2.3 North Pacific Variability

In a sequence of papers, Yeh and Kirtman (2003), Yeh and Kirtman (2004a) and Yeh and Kirtman (2004b) examined the simulated and observed North Pacific variability and its relationship to global climate variability (Yeh and Kirtman, 2004e). In particular, it was shown that most of the variability in the North Pacific is stochastically forced and that this stochastic forcing masks much of the response to remote tropical forcing.

2.2.2.4 Tropical Pacific Decadal Variability and ENSO

Yeh and Kirtman (2004c), Yeh and Kirtman (2004d), Yeh et al. (2004) and Moon et al. (2004) examined tropical decadal variability in both coupled model simulations and observations. The overarching result is that there are unambiguous relationships between the tropical Pacific mean state and ENSO variance in both the model and observations. This result implies that there is some fundamental non-linearity in the coupled system that cannot be accurately modeled as a linear auto-regression model with white noise forcing.

2.2.2.5 ENSO-Monsoon Interactions

The interactive ensemble provides an ideal framework for understanding the physical relationships between ENSO and the monsoon within the context of a CGCM without overwhelming interference from the noise in the climate system. Using the interactive ensemble and a new composite strategy, Wu and Kirtman (2003) separated ENSO-related and -unrelated monsoon variability. It was show that a weak (strong) monsoon enhances (weakens) an ongoing warm event in both the model and observations. In a complementary paper, Wu and Kirtman (2004a) examined how ENSO influences the monsoon particularly on biennial time scales. They found that the central-eastern equatorial Pacific SST anomaly affects the Indian monsoon by two processes: (i) a shift of large-scale east-west circulation across the equatorial Indian-Pacific Oceans and (ii) a Rossby wave response over the northeastern Indian Ocean and western North Pacific.

Wu and Kirtman (2004b) and Wu and Kirtman (2004c) conducted a series of interactive ensemble, uncoupled AGCM and simple model simulations to diagnose the role of Indian Ocean coupling in maintaining the variability in the Indo-Pacific region. Higher (lower) Indian Ocean SST induces easterly (westerly) surface wind anomalies over the eastern Indian Ocean and western-central equatorial Pacific. Numerical experiments with a simple atmosphere model with specified SST forcing support the roles of imposed Indian Ocean SST anomalies. They also found that when the Indian Ocean is decoupled from the atmosphere, the Indian monsoon-ENSO relationship reverses. With additional numerical experiments this change was linked to the relationships between surface evaporation, surface wind, and SST in the North Indian Ocean. They found that coupled air-sea interactions were essential in capturing the observed variability.

2.2.2.6 Diagnosing Coupled Model Errors

Kirtman et al. (2004) extended the interactive ensemble approach to develop a new procedure for coupled GCM sensitivity studies. Here the focus is on coupled models, which do not use any empirical corrections at the air-sea interface (i.e., no anomaly coupling or flux corrections). The purpose of the sensitivity experiments was to understand why two different coupled models have such large differences in their respective climate simulations. The differences between the coupled models using the COLA and the NCAR (CAM2.0; Kiehl 2002 personal communication) AGCMs were examined. It was concluded that the tropical ocean warm bias in the COLA coupled model was due to errors in the heat flux, and that the erroneous westward shift in the tropical Pacific cold tongue minimum in the CAM2.0 model was due to errors in the momentum flux.

Wu et al. (2006) developed a simple diagnostic based on theoretical considerations to analyze how well coupled models capture local air-sea feedback. The procedure involves comparing the local simultaneous correlation between rainfall and evaporation and between SST and SST tendency among observations, CGCM simulations, and stand-alone AGCM simulations. The purpose is to demonstrate to what extent the model simulations can reproduce the observed air-sea relationship. While the model simulated correlation agrees with the observations in tropical eastern Pacific, large discrepancies are found in the subtropics, mid-latitudes, and tropical Indo-western Pacific Ocean regions. In tropical Indo-western Pacific Ocean regions and the mid-latitudes where the atmosphere contributes to the observed SST changes, the specified SST simulations produce excessive SST forcing, whereas the CGCM captures but somewhat overestimates the atmospheric feedback on the SST. In the subtropics, both the AGCM and CGCM produce unrealistic positive rainfall-SST correlation. In the tropical western-central Pacific and the north Indian Ocean, the CGCM simulated evaporation-SST correlation is opposite to the observed due to an excessive dependence of the sea-air humidity difference on the SST.

2.3 Interannual Predictability in the Atlantic and Indian Ocean Sectors

The focus of the tropical Atlantic and Indian Ocean studies is to understand the physical processes that generate the major characteristics of the observed interannual variability in these two oceans. Given the strong global effects of the ENSO cycle on the whole tropics, the question can be framed as an examination of the relative roles played by the regional air-sea interaction within each basin and the remote influences from outside forcing for both ocean basins. It has also been recognized that atmospheric fluctuations without strong periodicity, such as those from the mid-latitudes of both hemispheres, also exert strong influences on the tropical oceans by forcing sizable anomalies and provoking subsequent feedbacks. We would further like to evaluate the predictability of these essential processes, ranging from intraseasonal to interannual time-scales. Our goal is to design regional dynamical systems for seasonal-to-interannual forecasting, which correctly initializes the tendency of the regional ocean-atmosphere feedback and adequately responds to external influences.

We have made progress in the following aspects: First, we have designed a regional coupling strategy for using a CGCM to examine the relative importance of the regional air-sea interaction within each basin and the remote influences from outside forcing to generate the observed interannual variability, which have yielded interesting results in both oceans. Second, we have conducted extensive experiments to reduce the CGCM systematic bias, especially in the tropical Atlantic region, through empirical flux correction methods. Further studies have also been conducted to understand the model problems that cause the major bias. Third, accompanying the modeling study, we have analyzed the observational data to examine the characteristics of the anomalous variations in these regions.

Our modeling experiments have been conducted using a specific CGCM. The atmospheric component of the CGCM is a global spectral AGCM with a triangular truncation of the spherical harmonics at T42. Vertically, it is divided into 18 σ levels with higher resolution in the lower troposphere. The model has the same dynamical core as that of the NCAR CCSM3. The OGCM is a quasi-isopycnal model, developed by Paul Schopf. Its domain is the world ocean within 70°S-65°N with a horizontal resolution of 1° latitude x 1.25° longitude while the meridional resolution is increased to 0.5° within 10°S-10°N. Vertically, it has 14 active layers. The coupling between the OGCM and the AGCM is effected daily. A major effort has been made to demonstrate its capability to simulate the major patterns of variability in these two oceans, as well as in the tropical Pacific Ocean. More recently, we have been using this CGCM for experimental hindcasts starting from real-time ocean-atmospheric initial states from the NCEP atmospheric reanalysis and our own oceanic data assimilation product.

2.3.1 Tropical Atlantic Variability

2.3.1.1 Intrinsic Variability

Tropical Atlantic variability (TAV) is composed of three major patterns of significant importance for variability and predictability of climate in the Atlantic sector (Fig. 2.3.1, left-hand column). They are the Southern Tropical Atlantic (STA) pattern with anomalous SST fluctuations extending from the Angolan coast to the central equatorial ocean; the Northern Tropical Atlantic (NTA) pattern centered near the northern African coast; and the Southern Subtropical Atlantic (SSA) pattern in the open subtropical ocean. Previous studies have suggested that both the regional air-sea coupling and remote forcing from outside the basin may affect the formation of these patterns and their variability.

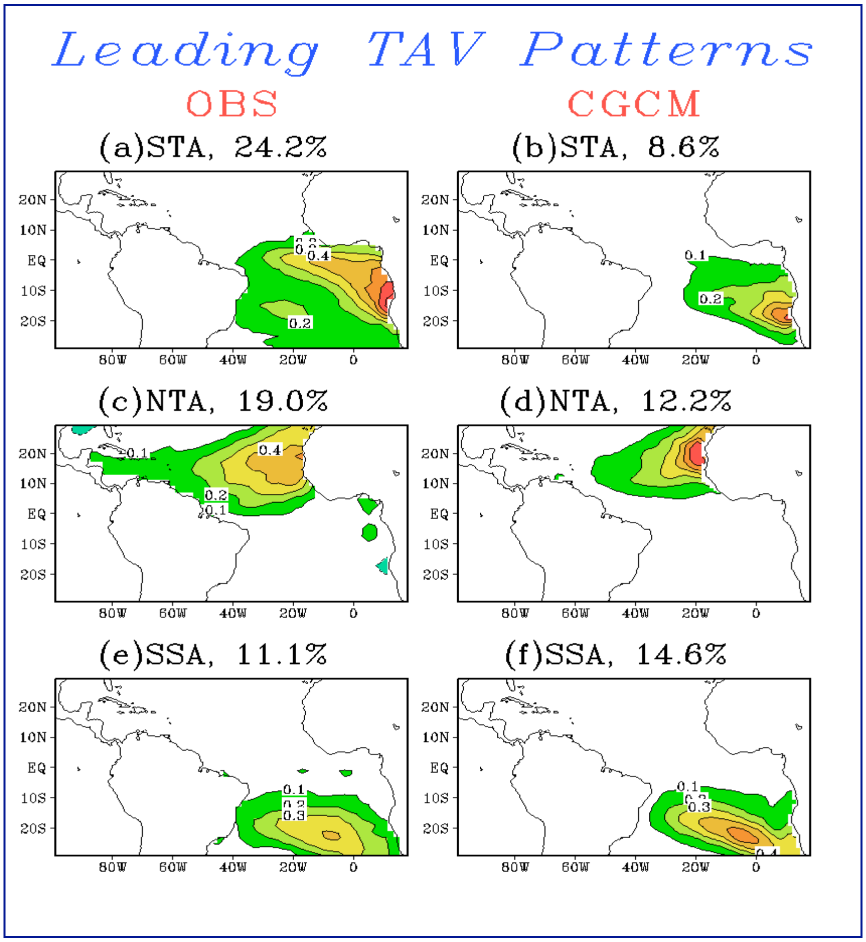

Figure 2.3.1*:*
The first three modes of the rotated empirical function of the seasonal mean SST anomalies in the tropical Atlantic Ocean (30°S-30°N) for observations in 1950-1998 (left-hand column) and a regional coupled simulation for 110-years (right-hand column). For each panel, the contour interval is 0.1°C with zero contours omitted. The corresponding principal component of each mode is normalized. Note that the CGCM modes are presented at reversed order of explained variances so that the modes are lined up with the observed ones with similar spatial patterns.

To isolate the influence of the regional air-sea coupling, Huang et al. (2004) used a specially designed global coupled ocean-atmosphere general circulation model, which eliminates air-sea feedback outside the Atlantic. Using a long simulation of 110 years, they found that this model realistically reproduces the major features of these observed patterns (Fig. 2.3.1, right-hand column). This suggests that these patterns originate from air-sea coupling within the Atlantic Ocean or by the oceanic responses to atmospheric internal forcing, in which there is no anomalous forcing external to the Atlantic Ocean. The effect of the Pacific ENSO seems to modulate the temporal evolution of the patterns by influencing atmospheric planetary waves propagating into the basin.

Several sensitivity experiments have been conducted to further examine the mechanisms of the anomalous SST patterns. The results demonstrate that both the NTA and SSA patterns are mainly associated with thermodynamic air-sea interactions while the STA pattern is likely to be more closely associated with the dynamical response of the equatorial and tropical ocean to the surface wind forcing. Moreover, results from a simulation with a time-independent correction term of the surface heat flux show that the simulated STA mode can be significantly strengthened and have a more realistic spatial structure if the model mean SST errors are reduced.

Huang and Shukla (2005) analyzed the evolution of the SSA and NTA patterns, both of which are linked with the fluctuations of the subtropical highs. The appearance of the SSA pattern is phase-locked to the annual cycle. Its enhancement in austral summer is associated with atmospheric disturbances from the south Atlantic during late austral spring. The extratropical atmospheric disturbances induce anomalous trade winds and surface heat fluxes on its northern flank, which generate SST anomalies in the subtropics during austral summer. The forced SST anomalies then change the local sea level pressure and winds, which in turn affect the northward shift of the atmospheric disturbance and cause further SST changes in the deep tropics during austral fall, which may be seen as a coupled advection process (Fig. 2.3.2).

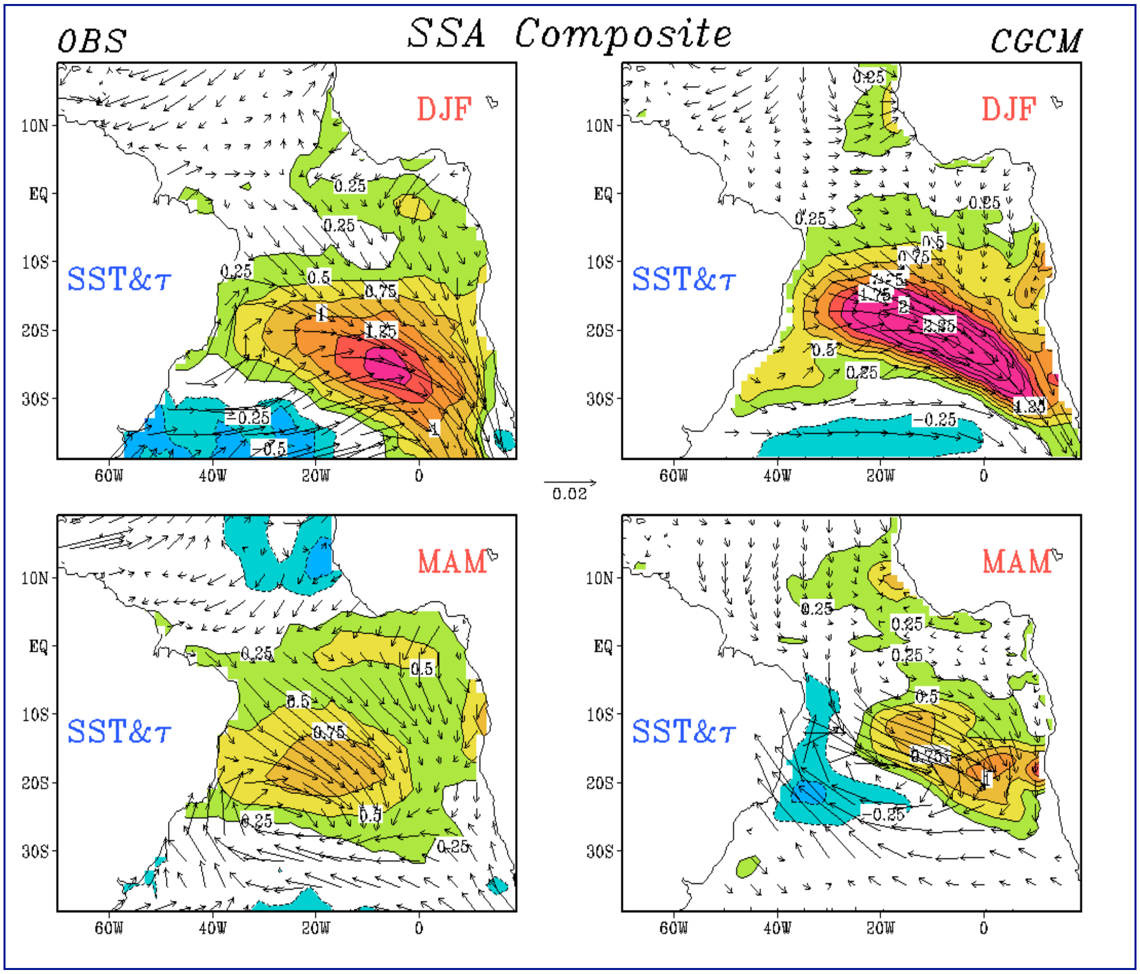

***Figure 2.3.2**: The composite events of the surface wind stress and SST anomalies southern subtropical Atlantic (SSA) pattern for the observations (left-hand panels) and the CGCM simulation (right-hand panels). The SST anomalies in the upper (lower) panels are seasonal averages for DJF (MAM). The corresponding wind stress is 3-month averages shifted one-month earlier. The contour interval for SST is 0.25°C with zero contour omitted. The length of the wind stress vector of 0.02Nm^{-2} is shown at the center of this figure.*

The NTA pattern is significant throughout the year. However, its center of action shows a significant seasonal migration. Like the SSA pattern, the NTA pattern in boreal winter-spring is usually associated with the heat flux change caused by extratropical atmospheric disturbances, such as the North Atlantic Oscillation. The SST anomalies then feed back on the tropical atmosphere and expand equatorward. From summer to fall, however, the NTA SST anomalies are likely to persist within the subtropics for more than one season after it is generated. Our model results suggest that this feature is associated with a local positive feedback between the NTA SST anomalies and the intensity of the atmospheric subtropical anticyclone from late boreal summer to early winter: A weakened subtropical high during the boreal summer induces warm SST in the northern subtropical Atlantic through reduced evaporative heat loss and weakened costal upwelling. On the other hand, the warm SST anomalies further weaken the subtropical high.

Analyzing a globally coupled 500-year simulation, Hu and Huang (2006a) further examined this air-sea feedback in the northern subtropical Atlantic Ocean during summer. In this work, they have investigated the evolution of the summer air–sea interaction in the North Atlantic Ocean and the physical processes involved using reanalysis data and model simulation. They found that an atmospheric disturbance over the North Atlantic in the preceding winter favors the buildup of the SST anomalies there during boreal summer, usually referred to as the North Atlantic horseshoe SST anomaly pattern, through modifying the northeast trade winds and changing ocean upwelling and downwelling. The changed ocean condition (SST anomaly, upwelling, and downwelling) further intensifies the atmospheric disturbance as a positive feedback. On the other hand, the thermal advection of the atmospheric disturbance tends to weaken the SST anomaly pattern in the following autumn and winter. The anomalous circulation associated with the air–sea interaction in the observations is characterized by a barotropic structure in the middle and high latitudes of the North Atlantic Ocean. The baroclinic component is enhanced in the model simulation, particularly in the seasons from summer to winter. The life cycle of the air–sea interaction is about one year in both the observations and simulations.

Most recently, Huang and Shukla (2006c) found that the SSA-type SST variability is a ubiquitous feature in the southern oceans. In contrast to their northern counterparts, active SST fluctuations occur in the open oceans in all three major basins, which are unattached to coastal processes. Using historical SST observations for 1950-2000, it was shown that these extra-tropical/subtropical SST anomalies have a tilted southwest-northeast dipole pattern in both the Atlantic and Indian Oceans and, to a certain extent, in the central and eastern Pacific. SST fluctuations in all basins show similar seasonal enhancement in austral summer. The long-term CGCM simulation reproduces some of these major features realistically in each of these ocean basins. A composite analysis of the objectively selected major events in the South Atlantic from the observations and the simulation shows that the anomalous SST pattern is initiated by mid-latitude atmospheric fluctuations. Through a coupled air-sea feedback, the center of the subtropical branch of the SST anomalies can shift towards the tropics in the next season.

2.3.1.2 Remotely Forced Variability

Parallel to the regional coupled simulation reported by Huang et al. (2004), Huang (2004) conducted an ensemble of eight hindcasts using an ocean-atmosphere general circulation model fully coupled only within the Atlantic basin, with prescribed observational SST for 1950-1998 in the global ocean outside the Atlantic basin. The purpose of these experiments is to understand the influence of the external SST anomalies on the interannual variability in the tropical Atlantic Ocean. Statistical methods, including empirical orthogonal function analysis with maximized signal-to-noise ratio, have been used to extract the remotely forced Atlantic signals from the ensemble of simulations. It is found that the leading external source on the interannual time scales is the ENSO in the Pacific Ocean.

The ENSO signal in the tropical Atlantic shows a distinct progression from season to season. During the boreal winter of a maturing El Niño event, the model shows a major warm center in the southern subtropical Atlantic together with warm anomalies in the northern subtropical Atlantic. The southern subtropical SST anomalies is caused by a weakening of the southeast trade winds, which are partly associated with the influence of an atmospheric wave train generated in the western Pacific Ocean and propagating into the Atlantic basin in the southern hemisphere during boreal fall. In the boreal spring, the northern tropical Atlantic Ocean is warmed by a weakening of the northeast trade winds, which is also associated with a wave train generated in the central tropical Pacific during the winter season of an El Niño event. Apart from the atmospheric planetary waves, these SST anomalies are also related to the sea level pressure (SLP) increase in the eastern tropical Atlantic due to the global adjustment to the maturing El Niño in the tropical Pacific. The tropical SLP anomalies are further enhanced in boreal spring, which induce anomalous easterlies on and to the south of the equator and lead to a dynamical oceanic response that causes cold SST anomalies in the eastern and equatorial Atlantic from boreal spring to summer. Most of these SST anomalies persist into the boreal fall season.

2.3.1.3 Systematic Bias

2.3.1.3a Empirical Flux Correction

One of the problems with CGCM simulations is a systematic bias to excessively shift southward the model inter-tropical convergence zone to around 10°S in boreal spring. In the coupled model, the air-sea feedback forms an artificial "warm pool" to the south of the equator, extending from the Brazilian coast nearly to the eastern boundary. This "warm pool" blocks the connection between the fluctuations in the equatorial and the southern part of the ocean. An interesting question is: How strongly does the CGCM bias affect its simulated variability? We speculate that the STA pattern is not adequately simulated due to this systematic problem. To address this issue quantitatively, we have artificially reduced the model systematic SST errors through an empirical correction. The procedure is to first calculate annual mean SST from a long-term coupled experiment and its difference from the observations. Then a heat flux correction term of 15 W m^{-2} per degree of mean SST error is specified in a simulation to adjust the surface heat flux into the OGCM (to be referred to as the 1st correction experiment). A "2nd correction" experiment is also done to further reduce the mean wind stress errors in the 1st correction run (Huang et al., 2005).

We found that these empirical corrections are quite effective in eliminating the surface wind and SST errors in the tropical Atlantic Ocean. Figure 2.3.3, top right, shows the annual mean surface wind stress and SST errors from the uncorrected GCM simulation and the 1st and 2nd correction experiments. It is apparent that simply putting a time fixed mean surface heat flux field into the ocean eliminates most of the mean SST errors of the original run (Fig. 2.3.3, bottom left), which are around 2.5°-3°C in the southeastern Atlantic off the African coast. Moreover, simply correcting SST errors also leads to a reduction of the wind stress errors within most of the basin if we compare Figs. 2.3.3, top right, and 2.3.3, bottom left. Especially of note, the northwest wind stress errors over the ocean from the equator to 10°S in Fig. 2.3.3, top right, have been reduced by more than a half (Fig. 2.3.3, bottom left). Further correction of the wind stress error in the 2nd experiment (Fig. 2.3.3, bottom right) slightly reduces the errors in both mean SST and wind stress further in most of the places except near the eastern boundary around 15°S-20°S (Fig. 2.3.3, bottom right), where the negative SST errors have the opposite sign from those in the uncorrected GCM run, which implies an over-correction in this region.

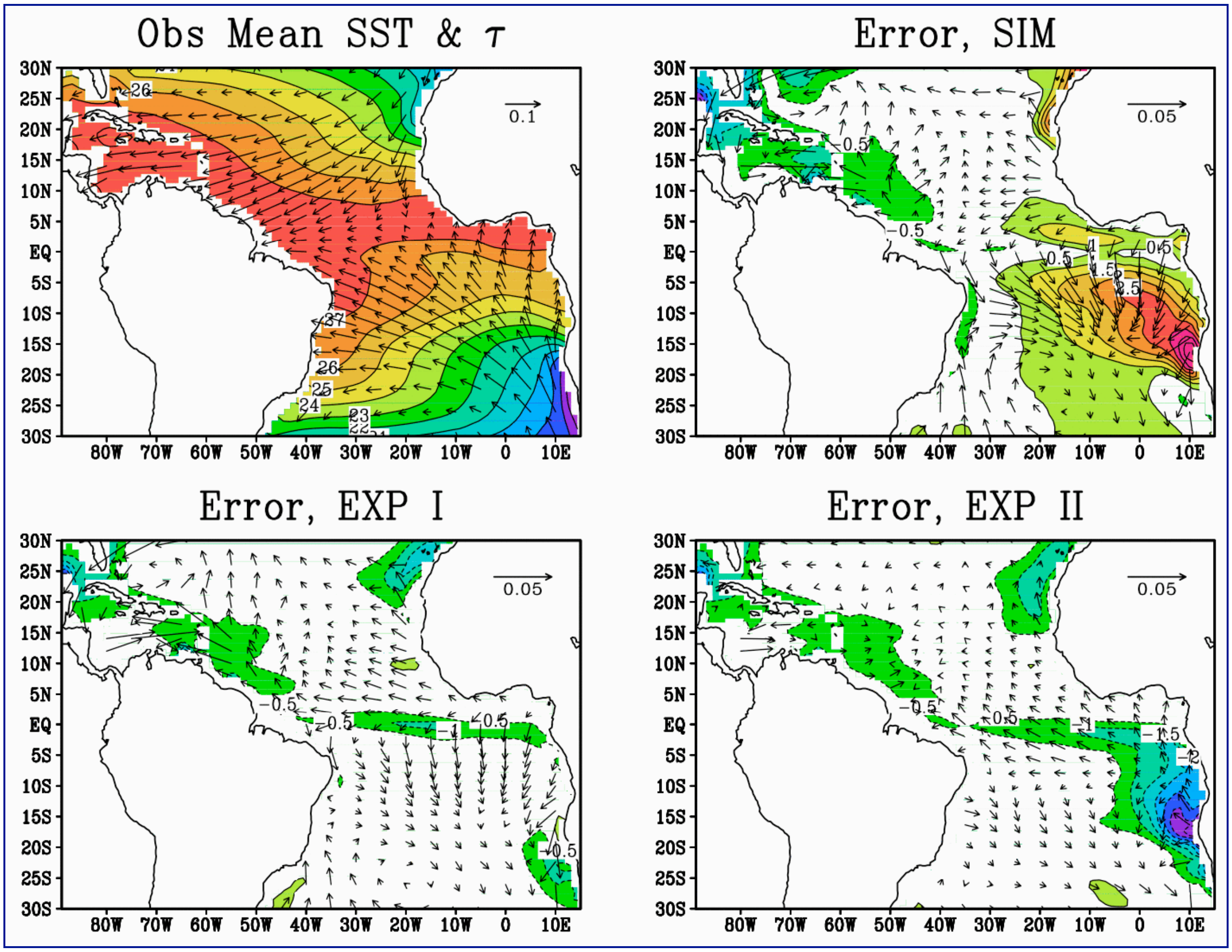

***Figure 2.3.3**: (top left) The observed annual mean SST and surface wind stress. The errors of the mean SST and wind stress are shown from long-term simulations of the regional coupled CGCM without flux correction (top right), with mean heat flux correction (1st correction experiment, panel (bottom left) and panel (bottom right) with additional momentum flux correction (2nd correction experiment*

Although the heat flux correction is constant in time, it improves the annual cycle of the equatorial SST and wind stress. More importantly, with the improved mean zonal and meridional SST gradient, the interannual SST fluctuations in the southeastern Atlantic are enhanced. The anomalous events, especially those near the Angola/Benguela coast, can be more realistically simulated with respect to the spatial structures of the surface wind stress and SST anomalies in the heat flux corrected run (middle column, Fig. 2.3.4) than the original simulation (right column, Fig. 2.3.4) although it is still much weaker than the observed in strength. While the improvement is moderate, there is reason to expect that, with the further reduction of other model errors and the ultimate elimination of this model systematic error, our ability to simulate the TAV and dynamically forecast the tropical Atlantic climate from seasonal to interannual time scales can be improved significantly.

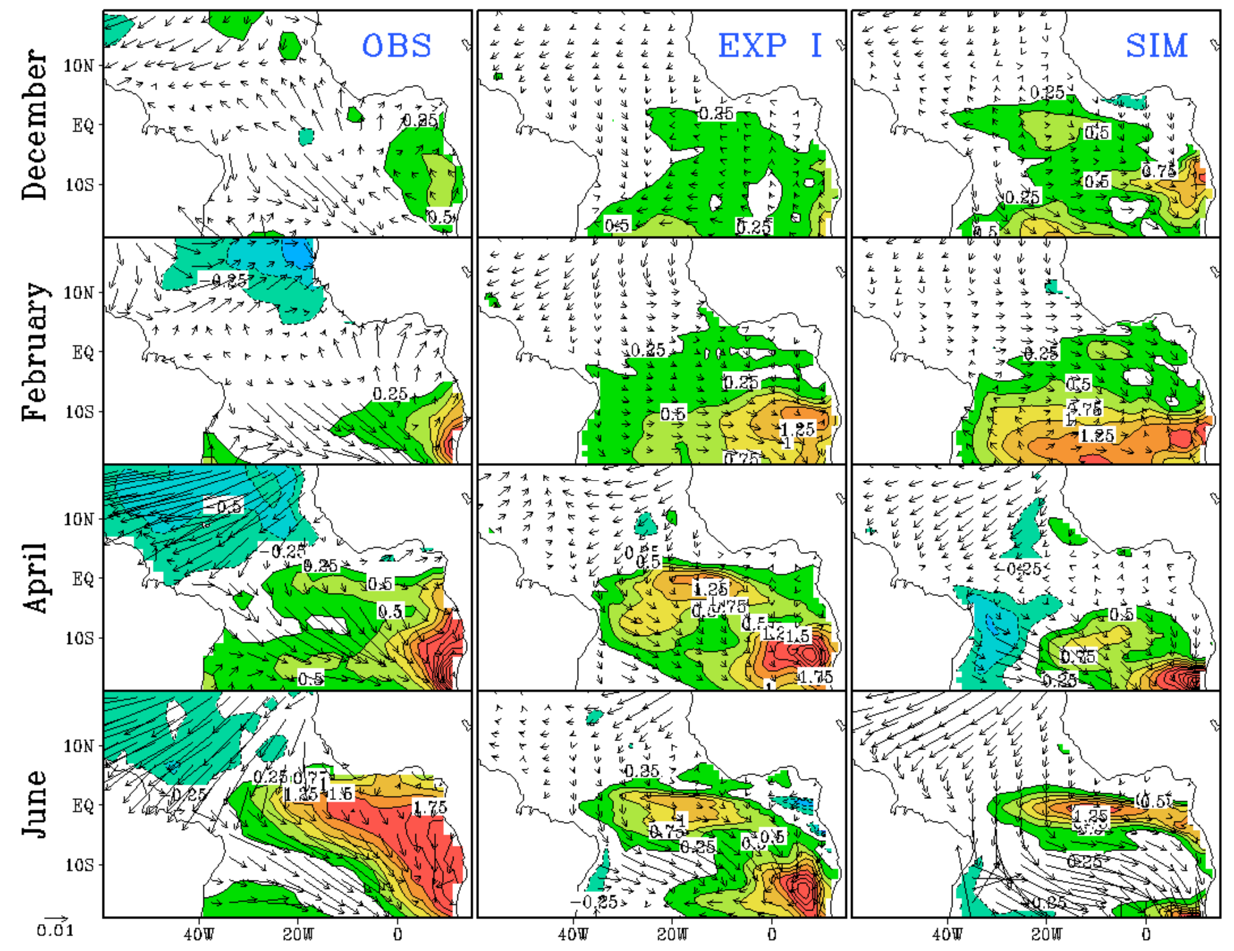

__Figure 2.3.4__: Composite anomalous events in the southeastern Atlantic Ocean. The observed composite based on anomalous events in 1950-1998 is shown in the left-hand column and a 100-year CGCM simulation with and without an empirical surface heat flux correction in the middle and right-hand columns. All composites are based on events chosen using the time series of their corresponding REOF modes in April. The variables shown are anomalies of SST and surface wind stress in February, April, June and August respectively in the panels from top to bottom in each column. The contour interval for SST is 0.25°C and the magnitude of the wind stress vector of 0.01 Nm^{-2} is shown at the bottom of the figure.

Analyzing a pair of sensitivity simulations using a global version of the CGCM, Manganello and Huang (2006) showed significant improvement of the mean SST state in the eastern Pacific Ocean if a heat flux correction is implemented. Along with the SST, distributions of surface wind stress and precipitation are also improved in these regions. As a result, the corrected mean climate exhibits stronger asymmetry relative to the equator. Due to the improvement of the model mean state, the annual cycles of the SST and surface wind stress in the eastern equatorial Pacific become more realistic as a result of enhancement of their annual, rather than semi-annual, harmonics. The annual cycle of precipitation in the eastern Pacific is also improved due to more realistic seasonal SST variations in this region. Both runs simulate interannual variability in the tropical Pacific with some characteristics of ENSO. However, in the CGCM without flux adjustment, the phase locking of ENSO to the annual cycle is unrealistic; ENSO events exhibit some eastward propagation at the equator and show a double-peak feature in the east connected to two distinct pulses in the zonal wind stress in the west. In the model with flux adjustment, phase locking to the annual cycle is reproduced remarkably well, likely due to more realistic seasonal evolution of the mean state. SST anomalies exhibit a standing mode at the equator, and the development of ENSO events at the equator is also more realistic. On the other hand, the simulated interannual variability is weaker and the timescale of ENSO events is too long compared to the observations.

2.3.1.3b Bias in Climate Hindcasts

Since significant systematic errors in the tropical Atlantic Ocean are common in state-of-the-art coupled ocean-atmosphere general circulation models, Huang et al. (2006) used a set of ensemble hindcasts from the NCEP CFS to examine the initial growth of the coupled model bias. These CFS hindcasts are nine-month integrations starting from perturbed real-time oceanic and atmospheric analyses for 1981-2003. The large number of integrations from a variety of initial states covering all months provides a good opportunity to examine how the model systematic errors grow.

The monthly climatologies of ensemble hindcasts from various initial months are compared with both observed and analyzed oceanic and atmospheric datasets. Our analyses show that two error patterns are dominant in the hindcasts. One is the warming of the SST in the southeastern tropical Atlantic Ocean. This error grows faster in boreal summer and fall and peaks in November-December at about 2°C in the open ocean. Fig. 2.3.5a presents the evolution of the SST bias averaged in the area within 5°S-15°S and 10°W-10°E for hindcasts with different lead month 0 (LM0). Each segment of the curves represents the evolution of the SST error starting from its LM0 and ending nine months later. The figure shows that all hindcasts with LM0 from March to November peak in October-January near 1.6°C. The hindcast with LM0 in December also peaks in January but with lower maximum value (1.2°C). Since the error curves with LM0 from April to September converge in November-December, the errors of the hindcasts starting from later months grow more quickly. This tendency can be seen clearly from the dependence of the error growth in the 1st month of the hindcasts on season, represented by the starting points of the error curves.

This systematic bias is visible in not only the ensemble mean but also the individual runs. Fig. 2.3.5b shows the average real-time SST errors in the same area for 330 individual hindcasts starting from the month of June in 1982-2003. Although there is a substantial spread of the SST error among these runs with a standard deviation of about 0.5°C from their mean, in every lead month of the hindcast a warming tendency clearly stands out for most of the cases. In fact, no matter what the initial errors are, all runs have a positive SST error in this area from September to January. Therefore, the bias in the southeastern tropical Atlantic identified from the ensemble means is a robust feature of the model. Our case examinations also find that, due to this bias, the spread within an ensemble hindcast usually cannot encompass the observational target after August (not shown).

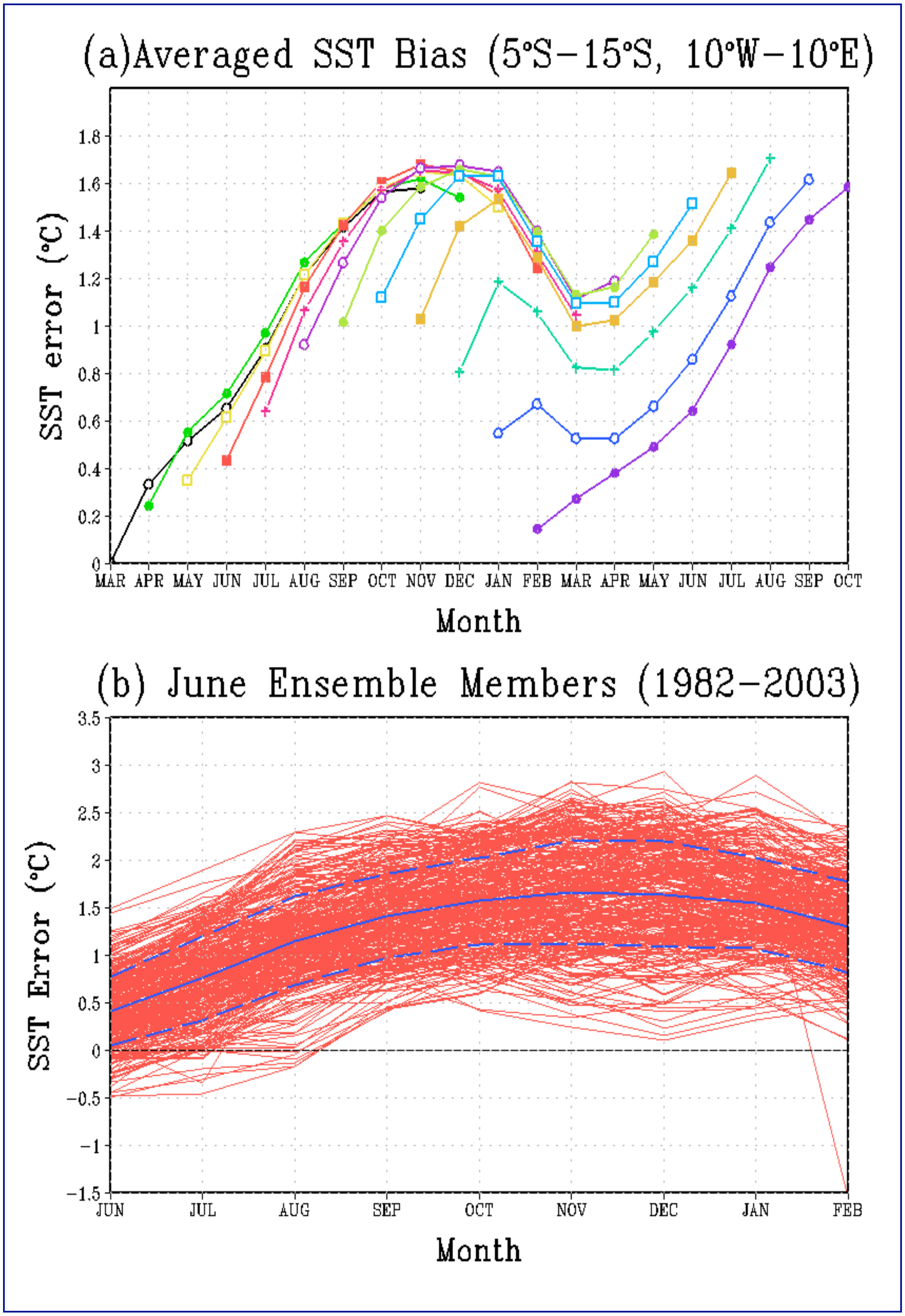

Figure 2.3.5*: Panel (a) shows the SST biases (oC) averaged within the rectangle area in Fig.2g (5°S-15°S, 10°W-10°E) for the ensemble mean CFS hindcasts from different LM0s. Each curve starts from its LM0 and spans nine months. The red curves in panel (b) shows the averaged SST errors for all members of the hindcasts starting from June for 1982-2003. The solid blue curve shows the average and the dashed curves shows the limits of one standard deviation above and below the average.*

Further analysis shows that this bias is caused by an excessive model surface shortwave radiative flux in this region, especially in boreal summer and fall. The excessive radiative forcing is in turn caused by the model's inability to reproduce the observed amount of low cloud cover in the southeastern ocean and its seasonal increase. According to a comparison between the seasonal climatologies from the CFS hindcasts and a long-term simulation of the atmospheric model forced with observed SST, the CFS low cloud and radiation errors are inherent to its atmospheric component. On the other hand, the SST error in CFS is a major cause of the model's southward bias of the intertropical convergence zone (ITCZ) in boreal winter and spring. An analysis of the SST errors of the six-month ensemble hindcasts by seven coupled models in the DEMETER project shows that this SST error pattern is common in coupled climate hindcasts (Fig.2.3.6).

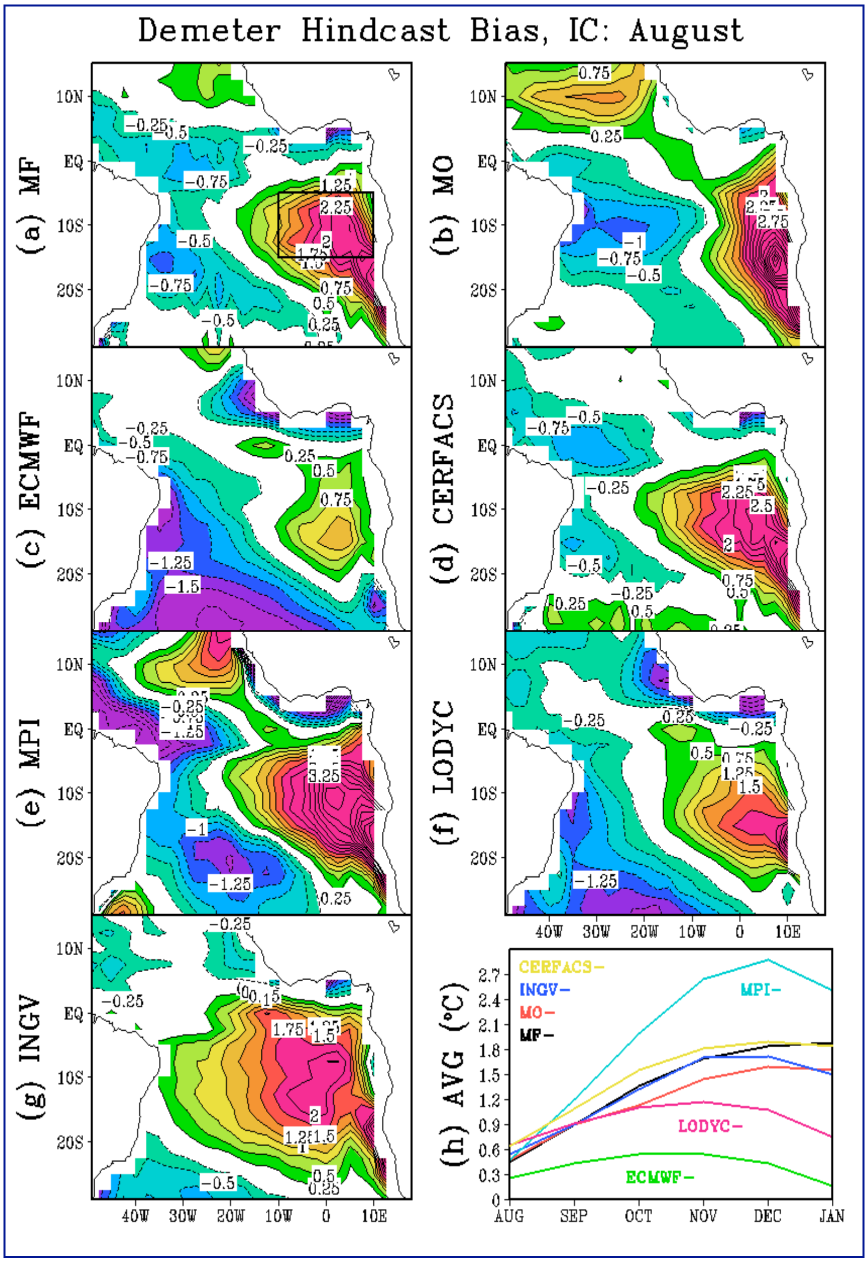

Figure 2.3.6*: The SST bias in November from DEMETER ensemble hindcasts initialized at August 1st, 1981-2001 for (a) MP, (b) MO, (c) ECMWF, (d) CERFACS, (e) MPI, (f) LODYC, and (g) INGV. The contour interval in (a)-(g) is 0.25oC with zero lines omitted. Panel (h) shows the averaged SST bias as in Fig.4 (also shown by the rectangle in Fig.5a) for the evolution from August to January.*

The second error pattern is an excessive deepening of the model thermocline depth to the north of the equator from the western coast toward the central ocean. This error grows fastest in boreal summer. It is forced by an overly strong local anticyclonic surface wind stress curl and is in turn related to the weakened northeast trade winds in summer and fall. The thermocline error in the northwest delays the annual shoaling of the equatorial thermocline in the Gulf of Guinea remotely through the equatorial waveguide.

2.3.1.4 Observational Analysis

Accompanying our modeling study, we have conducted several diagnostic studies using long-term observational datasets.

2.3.1.4a Interannual Variability of the Tropical Atlantic SST Gradient

The variability of the SST gradient is at the center of current theories of TAV. However, as far as we know, this critical variable has not been analyzed objectively using statistical methods. Hu and Huang (2006c, 2006d) systematically studied the leading modes of interannual variability of SST gradients in the tropical Atlantic and their associated physical processes using different EOF analysis techniques. Our results demonstrate that, close to the equator, the anomalous SST gradient directly forces the wind stress anomalies, and its leading patterns are consistent with the leading air-sea coupled modes described by previous studies.

In particular, it was found that the leading modes of the SST gradient (computed from the combined EOF of zonal and meridional components) in boreal spring (March – May or MAM) and summer (June – August or JJA) involve strong air-sea interaction and the SST, wind stress, SST zonal and meridional gradients display consistent spatial distribution patterns in MAM and JJA (see Fig. 2.3.7). The spatial distribution of the dominant mode in MAM is a see-saw pattern, reflecting the opposite variation of the meridional SST gradient between the subtropical and tropical North Atlantic, which results from a coherent warming or cooling with maxima along 10-15°N (left panels of Figure 2.3.7). This mode is dominated by the wind-evaporation-SST (WES) feedback. The feedback persists a longer time in the western Atlantic than in the eastern. The contribution to the SST variation is mainly from latent heat flux. The surface long-wave and short wave cloud radiative forcings are mainly determined by low cloud cover variations. It was also found that this thermodynamic mode peaks in MAM and becomes weak in the following JJA. A similar thermodynamic mode appears farther north in boreal autumn and its life cycle is shorter than the one in MAM.

In contrast to the leading mode in MAM, the leading mode in JJA is a dynamical air-sea feedback mode, reflecting a coherent warming or cooling pattern extending from the Angolan coast toward the equator in the Gulf of Guinea (right panels of Fig. 2.3.8). For anomalies peaking in JJA, the warming (cooling) is initiated near the Angola coast in MAM. This suggests that SST anomalies along the coast and near the equator are physically connected. The air-sea interaction along the coast may be a major factor to trigger the development of SST anomalies near the equator, which are intensified by local positive feedbacks that may include both Bjerknes and Ekman processes. In return, the warming or cooling near the equator weakens the SST anomalies along the coast by changing the direction of the anomalous wind. Slow westward Rossby wave propagation may also play a role in stimulating the equatorial feedback. The thermodynamic processes affect the evolution of this mode. On average, the net surface latent heat flux anomalies are the leading damping factor, and the net surface sensible heat flux plays the same role on a smaller scale, while the net surface short (long) wave radiation heating has a negative (positive) contribution to the SST variation. However, although on average the surface heat flux damps the SST anomalies, the role played by the heat flux varies across regions and components. Spatially, the latent and sensible heat flux as well as the long wave radiation damp air-sea coupling in the eastern south Atlantic near the Gulf of Guinea and amplify the coupling in the western equatorial ocean. The situation is the opposite for the solar radiation.

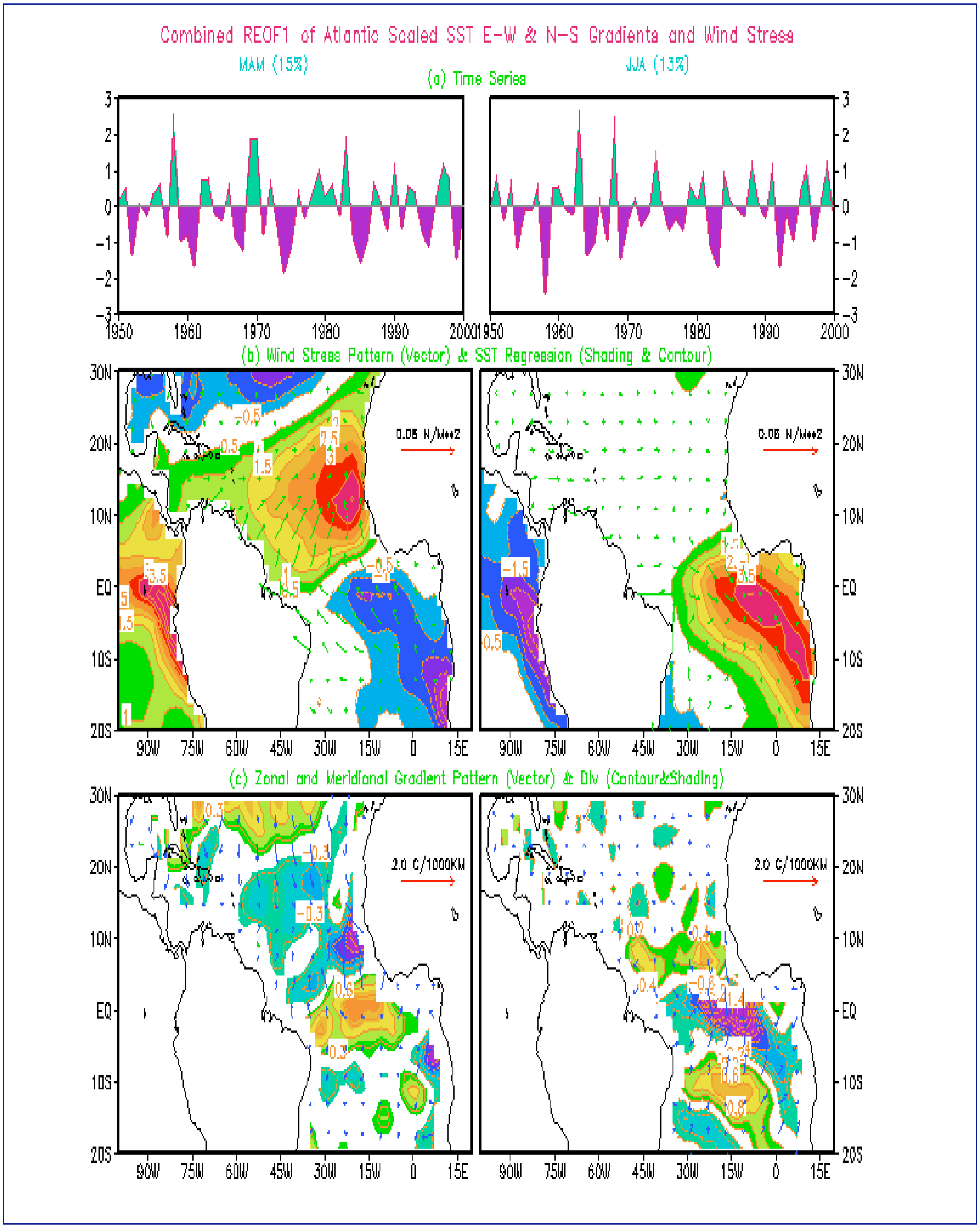

***Figure 2.3.7**: REOF1 of combined SST zonal and meridional gradients, and wind stress in MAM (left panels) and JJA (right panels). (a): the time series, (b): spatial pattern of wind stress (vector) and SST regressions onto the time series (contour and shading); (c) spatial pattern of zonal and meridional SST gradients (vectors) and their divergences (contour and shading).*

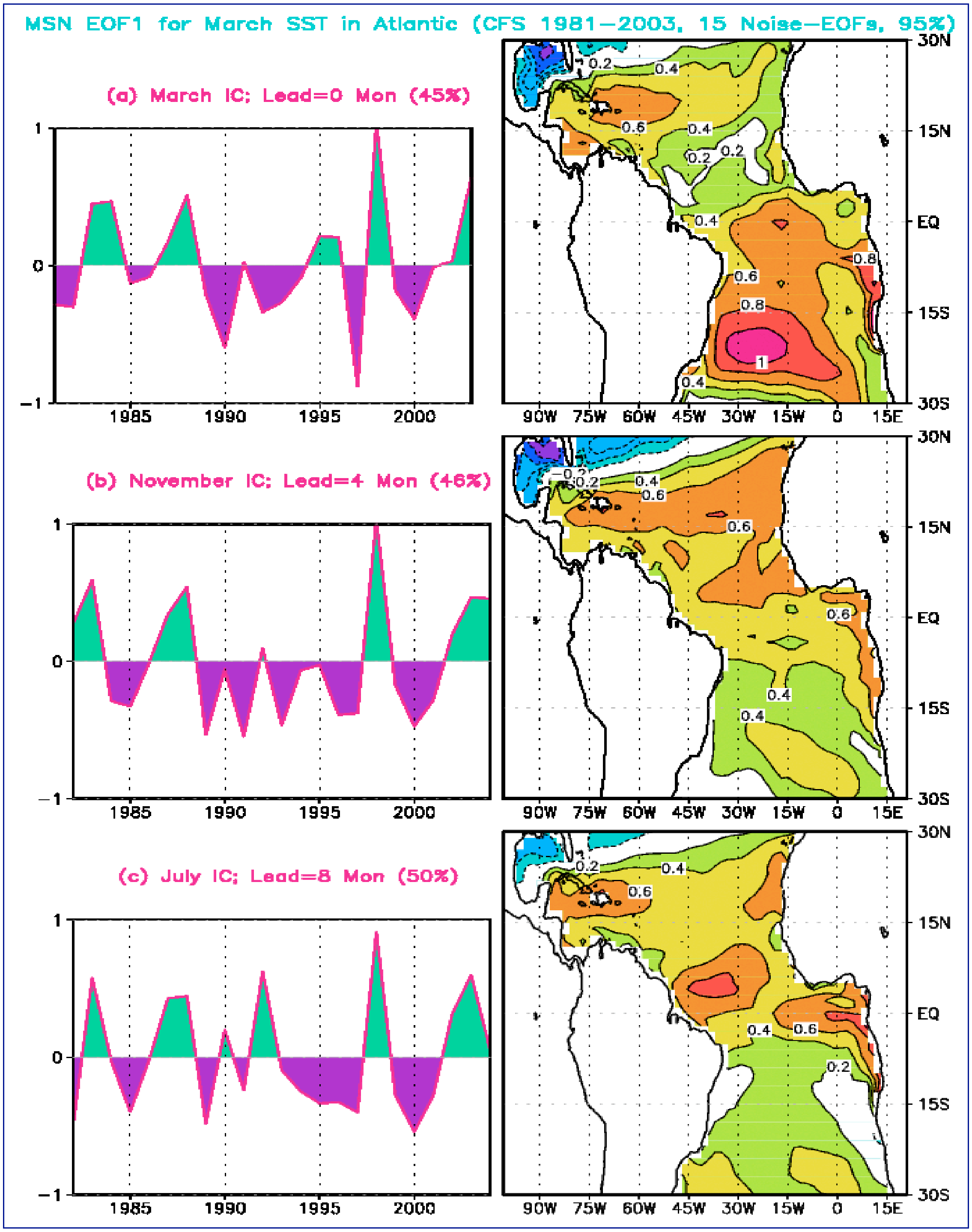

Figure 2.3.8: *Time series (left column) and spatial patterns (right column) of MSN EOF1 of March SST, (a) lead 0 month and March IC, (b) lead 4 months and November IC, and (c) lead 8 months and July IC. The contour interval is 0.2, the zero lines are omitted, and the shading is for values larger than 0.2 or smaller than -0.2 for the spatial patterns. The real magnitude of the SST anomalies (°C) can be restored by multiplying the values in the spatial patterns with the corresponding time series. The percentage of the explained variance for the ensemble mean anomalies is indicated in each panel.*

2.3.1.4b The NAO in Early Winter and Atlantic SST Anomalies

It is still unclear if the North Atlantic Oscillation (NAO) is predictable on interseasonal time scales. Recently, Hu and Huang (2006b) found that, in most years, the NAO is unpredictable. They investigated the association of Atlantic SST anomalies with the early winter NAO. In this study, the NAO was represented by two indices in November, December, and January, that are based on previous studies. One is defined as the 500 hPa geopotential height difference between areal averages in low and high latitudes, while another is the SLP difference between two stations: Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland. These two indices are referred to as the regional mean and station indices, respectively. Although the two indices are highly correlated, they exhibit clearly different statistical associations with the antecedent Atlantic SST anomaly. The regional mean NAO index in early winter is significantly correlated with a tripole pattern of SST anomalies in the Atlantic up to the preceding spring. Therefore, predictability may be claimed for up to 7-9 months. However, there is little predictability for the station NAO index beyond two months before the early winter, based on the SST anomaly. Further composite analysis suggests that the interseasonal potential predictability of the NAO shown in the regional mean index mainly results from the contribution of a few years, that are not strong anomaly years according to the station index. Therefore, little predictability on interseasonal time scales is suggested for most of the NAO anomaly years and the potential predictability displayed in association with the regional mean index mainly results from the average of a few anomaly years. They also found that the SST anomaly contribution to the NAO predictability comes mostly from the north Atlantic and northern subtropical Atlantic. The association of equatorial Atlantic SST anomaly with the NAO for both indices is insignificant. There is no linear connection between the tropical Atlantic SST anomaly and the tripole SST anomaly pattern. In addition, our analysis shows that the tropical and north Pacific SSTA may be a factor affecting NAO predictability.

2.3.1.4c Cloud-SST Feedback in The Eastern Tropical Atlantic Ocean

Using satellite-based cloud measurements for 1984-2004, Huang and Hu (2006) examined the interannual variability of the low-level cloud cover over the tropical Atlantic Ocean in austral winter (June-July-August, JJA). They found that the leading pattern of the low cloud anomalies in this season is a modulation of the climatological center of the cloud cover over the southeastern tropical Atlantic Ocean off the Angola and Benguela coasts. The fluctuation of cloud amount there occurs on both interannual and longer time scales.

The relationship between this low cloud anomalous pattern and basin-wide ocean-atmosphere anomalies is studied through a composite analysis based on the objectively selected major low-cloud deficit and excess years. For the composites, we intentionally used datasets mainly based on satellite measurements for the past one to two decades to minimize the potential influences of the bias in the model-based ocean-atmosphere analyses. The composites show that the JJA anomalous cloud pattern is strongly influenced by the SST anomalies of the equatorial and southeastern tropical Atlantic Ocean in the previous summer. The anomalous surface warm events off the southwestern coast of Africa near 15°S in January and February are usually initiated dynamically by remote forcing from the westerly wind anomalies over the western equatorial Atlantic, preceding the cloud anomalies. During the next few months, the warm water spreads into the southeastern tropical Atlantic Ocean and is conducive to less low-cloud cover in the subsequent JJA. The reduced low cloud cover in turn forces positive SST tendency in a larger area of the southeastern Atlantic Ocean by changing the amount of the local solar radiation reaching the sea surface. In June and July, this process moves the major center of the SST anomalies away from the coast and closer to the equator when the coastal process weakens. The low cloud-radiation-SST feedback also plays a role in the slow westward expansion of the SST anomalies in late austral winter and spring. Overall, the influence of the cloud fluctuation is an important component in the evolution of the southeastern tropical Atlantic anomalous events.

2.3.1.5 CFS Hindcast Skill in the Tropical Atlantic Ocean

Hu and Huang (2006e) investigated the most predictable pattern in the CFS in the tropical Atlantic Ocean using the CFS 1981-2003 hindcasts. The most predictable patterns are isolated by an empirical orthogonal function analysis with maximized signal-to-noise ratio (MSN EOF). The MSN EOF method derives patterns that optimize the signal-to-noise ratio from all ensemble members. This method minimizes the effects of noise in a moderate ensemble size. An ensemble mean is supposedly composed of a forced and a random part, which may be attributed respectively to the prescribed external boundary conditions and the unpredictable internal noise. The leading MSN EOF mode is the one with the maximum ratio of the variance of the ensemble mean to the deviations among the ensemble members. The most predictable pattern of SST in March has the same sign in almost the whole tropical Atlantic (Fig. 2.3.8). The corresponding pattern in March is dominated by the same sign for geopotential height at 200 hPa in most of the domain and by significant opposite variation for precipitation between the northwestern tropical North Atlantic and the regions from tropical South America to the southwestern tropical North Atlantic (not shown). These predictable signals mainly result from the influence of ENSO. The significant values in the most predictable pattern of precipitation in the regions from tropical South America to the southwestern tropical North Atlantic in March are associated with excessive divergence (convergence) at low (high) level over these regions in CFS.

The predictive skill of CFS in the tropical Atlantic was also examined. The skill is measured by the SST anomaly correlation between the predictions and the corresponding analyses. On average, for predictions with initial conditions (IC) from all months, the predictability of SST is higher in the west than in the east. The highest skill is near the tropical Brazilian coast and in Caribbean Sea, and the lowest skill occurs near the eastern coast. Seasonally, the skill is higher for predictions with IC in summer or autumn and lower for those with IC in spring. CFS poorly predicts the meridional gradient in the tropical Atlantic Ocean. The superiority of the CFS predictions to the persistence forecasts depends on IC month, region, and lead-time. The CFS prediction is generally better than the corresponding persistence forecast when lead-time is longer than 3 months. For CFS, the predictive skill in the tropical Atlantic Ocean is largely determined by its ability to predict ENSO. This is due to the strong connection between ENSO and the most predictable patterns in the tropical Atlantic Ocean in the model. The higher predictive skill of tropical North Atlantic SST is consistent with the ability of CFS to predict ENSO on interseasonal time scales, particularly for the IC in warm months from March to October. In the southeastern ocean, the systematic warm bias is a crucial factor leading to the low skill in this region.

2.3.2 Tropical Indian Ocean Variability

The controlled CGCM experiments in the tropical Indian Ocean mirror those in the tropical Atlantic Ocean. Huang and Shukla (2006a) conducted a series of experiments using a coupled ocean-atmosphere general circulation model in regional-coupled mode, which permits active air-sea interaction only within the Indian Ocean to the north of 30°S, with SST prescribed over the rest of the world ocean. In this paper, we have analyzed an ensemble of nine simulations with the observed SST anomalies for 1950-1998 prescribed over the uncoupled region. The purpose of this study is to determine the major patterns of interannual variability in the tropical Indian Ocean that could be related to the global low frequency fluctuations, and to understand the physical links between the remote forcing and the regional coupled variations.

The ensemble coupled simulations with prescribed SST outside the Indian Ocean are able to reproduce a considerable amount of the observed variability in the tropical Indian Ocean during 1950-1998. The 1st EOF modes of the simulated upper ocean heat content (Fig. 2.3.9) and SST anomalies show structures that are quite consistent with those from the historical upper oceanic temperature and SST analyses. The dominant pattern of response is associated with an oceanic dynamical adjustment of the thermocline depth in the southwestern Indian Ocean. In general, a deepening of the thermocline in the southwest is usually accompanied by the enhanced upwelling and thermocline shoaling centered near the Sumatra coast. Further analysis shows that the leading external forcing is from ENSO, which induces an anomalous fluctuation of the atmospheric anticyclones on both sides of the equator over the Indian Ocean simultaneous with the evolving stage of an El Niño event in boreal summer. Apart from weakening the Indian monsoon, the surface equatorial easterly anomalies associated with this circulation pattern first induce equatorial and coastal upwelling anomalies near the Sumatra coast from summer to fall, which enhance the equatorial zonal SST gradient and stimulate intense air-sea feedback in the equatorial ocean. Moreover, the persistent anticyclonic wind curl over the southern tropical Indian Ocean, reinforced by the equatorial air-sea coupling, forces substantial thermocline change centered at the thermocline ridge in the southwestern Indian Ocean for all seasons. The significant thermocline change has profound and long lasting influences on the SST fluctuations in the Indian Ocean. These modeling results substantiate our previous results on the major roles played by thermocline dynamics and air-sea coupling in ENSO-induced Indian Ocean variability.

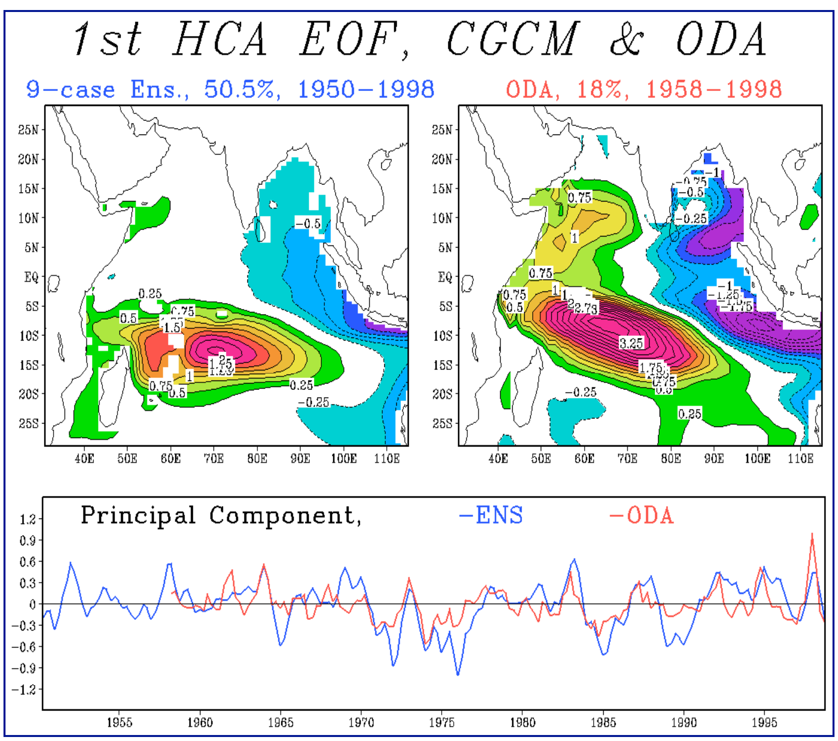

Figure 2.3.9*:*
The 1st EOF modes of the upper ocean heat content anomalies in the tropical Indian Ocean from a 9-case ensemble of a regional coupled GCM with observed SST anomalies for 1950-1998 prescribed outside the basin (upper left), and the COLA ocean analysis for 1959-1998 (upper right). The principal components are shown in the lower panel for the CGCM (blue) and observations (red) with correlation 0.6. The contour interval in the upper panels is 0.25°C with zero lines omitted. The time series are normalized to have a unit maximum magnitude.

It should be noted that ENSO forcing is not the only way this kind of basin-wide Indian Ocean fluctuation can be generated. In order to understand the intrinsic mechanisms of the interannual variability in the tropical Indian Ocean, Huang and Shukla (2006b) conducted two long simulations using a coupled ocean-atmosphere GCM; one with active air-sea coupling over the global ocean and the other with regional coupling restricted to the Indian Ocean to the north of 30°S while the climatological monthly SST is prescribed in the uncoupled oceans to drive the atmospheric circulation. The major spatial patterns of the observed upper ocean heat content and SST anomalies can be reproduced realistically by both simulations, suggesting that they are determined by intrinsic coupled processes within the Indian Ocean.

In both simulations, the interannual variability in the Indian Ocean is dominated by a tropical mode and a subtropical mode. The tropical mode is characterized by a coupled feedback among thermocline depth, zonal SST gradient, and wind anomalies over the equatorial and southern tropical Indian Ocean, which is strongest in boreal fall and winter. The tropical mode simulated by the global coupled model reproduces the main observational features, including a seasonal connection to the model ENSO. The ENSO influence, however, is weaker than that in a set of ensemble simulations described in Part I of this study, where the observed SST anomalies for 1950-98 were prescribed outside the Indian Ocean. We concluded that ENSO can modulate the temporal variability of the tropical mode through an atmospheric teleconnection. Its influence depends on the ENSO strength and duration. The stronger and more persistent El Niño events in the observations extend the life span of the anomalous events in the tropical Indian Ocean significantly. In the regional coupled simulation, the tropical mode is still active, but its dominant period is shifted away from that of ENSO. In the absence of ENSO forcing, the tropical mode is mainly stimulated by an anomalous atmospheric direct thermal cell forced by the fluctuations of the northwestern Pacific monsoon. The unique feature of the observed ENSO influence is that, because of the high persistence of the atmospheric remote forcing from boreal summer to winter, the life span of the thermocline anomalies in the southwestern Indian Ocean is generally longer than that generated by regional coupled processes.

The subtropical mode is characterized by an east-west dipole pattern of the SST anomalies in the southern subtropical Indian Ocean, which is strongest in austral fall. The SST anomalies are initially forced by surface heat flux anomalies caused by the anomalous southeast trade wind in the subtropical ocean during austral summer. The trade wind anomalies are in turn associated with extratropical variations from the southern annular mode. A thermodynamic air-sea feedback strengthens these subtropical anomalies quickly in austral fall and extends their remnants into the tropical ocean in austral winter. This subtropical variability is independent of ENSO.

2.4 Predictability of Monsoons

Research on monsoons at COLA has focused on understanding the variability and predictability of the South Asian monsoon and the South American monsoon on both intraseasonal and interannual time scales. These studies are based on observations as well as general circulation model results.

2.4.1 South Asian Monsoon

During the current research period, the studies using observational data have focused on the space-time structure of the intraseasonal variability of the monsoon region covering the

Indian subcontinent and the Indian Ocean and on the factors that may determine the interannual variability and the predictability of the seasonal mean monsoon. The relation between the Indian monsoon rainfall and global climate variability was reviewed, and the validity of statistical prediction of seasonal rainfall based on global climate variables was examined. The modeling studies consist of assessing the performance of COLA AGCM forced with observed SST in simulating the South Asian monsoon, analyzing the monsoon variability in simulations by the NCEP CFS, and demonstrating the importance of coupled atmosphere-ocean interaction for seasonal prediction.

2.4.1.1 Intraseasonal Variability and Predictability of Seasonal Mean Monsoon

The optimism for long-term prediction of the monsoon and improved predictability of the seasonal mean monsoon by models is based on the hypothesis of Charney and Shukla (1981) according to which a large part of the monsoon variability is determined by the slowly varying boundary conditions such as the SST, soil moisture and snow cover. This basic hypothesis received further support from the work of Straus and Krishnamurthy (2006), who identified a three-dimensional circulation structure based on seasonal mean winds at 850 and 200 hPa whose temporal variation is more highly correlated (at the 0.75 level) with area-integrated Indian Monsoon Rainfall (IMR) than circulation indices proposed in the past. The pattern is the leading EOF of 56 years (1948-2003) of summer mean reanalysis rotational wind components that were de-trended.

The correlation of the corresponding time series (PC) with global seasonal mean SST is strong and negative over the eastern equatorial Pacific, but positive in a surrounding horseshoe like region. Significant negative correlation occurs in the northwestern Indian Ocean. The lag/lead correlation between the NINO3 SST index and PC-1 is similar to but stronger than the NINO3 / IMR correlation.

An observational study in the previous research period further proposed that the interannual variability of the seasonal mean monsoon rainfall is a combination of a large-scale persistent mean component and a statistical average of intraseasonal variations and that the success in prediction depends on the relative strengths of these components (Krishnamurthy and Shukla 2000). Strong support for this conceptual model has been provided by current studies that have investigated the space-time structure of daily rainfall, OLR and horizontal winds over the South Asian monsoon region.

Multi-channel singular spectrum analysis (MSSA) of observed daily rainfall anomalies over India and daily OLR anomalies over the larger South Asian monsoon region has revealed the existence of two dominant intraseasonal modes and two dominant seasonally persisting modes (Krishnamurthy and Shukla 2006a, 2006b). The intraseasonal modes are nonlinear oscillations, with broad spectra centered at 45 and 28 days, which combine to form active and break periods of the monsoon. Their large spatial structure extends to the western Pacific (Fig. 2.4.1). In addition to in-situ expansion of convective zones, the 45-day mode shows northeastward propagation while the 28-mode shows northwestward propagation. However, these intraseasonal modes contribute very little to the seasonal mean.

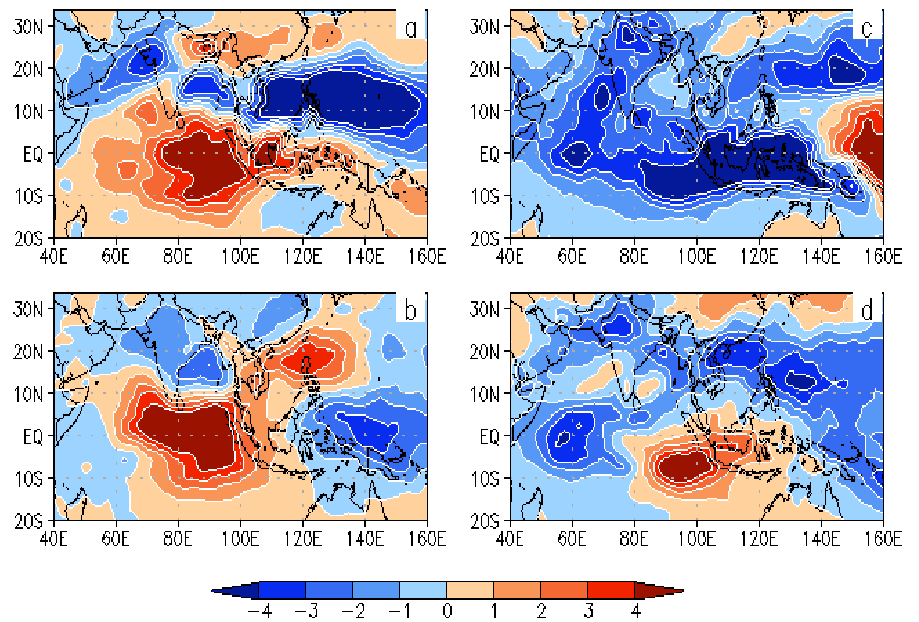

***Figure 2.4.1**: Spatial structure o the reconstructed components of the eigenmodes obtained from MSSA of daily OLR anomalies over the Indian monsoon region: (a) 45-day mode, (b) 28-day mode (c) persistent ENSO mode, and (d) persistent dipole mode. Units are arbitrary.*

The seasonal mean monsoon is mainly determined by the two standing modes (with red spectra), one of which has the ENSO pattern and the other has the Indian Ocean dipole pattern (Fig. 2.4.1). In a given year, each of these two patterns persists throughout the monsoon season with more or less the same sign. The relative strengths of these persisting patterns seem to be important in determining the seasonal mean (Fig. 2.4.2). For example, during the 1987 El Niño year, both patterns contributed to the weak seasonal mean monsoon while during the 1988 La Niña year only the ENSO pattern determines the seasonal mean. More interestingly, during the strong El Niño year of 1997, the large positive contribution from the ENSO pattern was compensated by a large negative contribution from the dipole pattern, indicating that the monsoon-ENSO relation was still robust during 1997. The success in predicting the seasonal mean monsoon depends on the relative roles of these persisting patterns as well as on the intraseasonal modes.

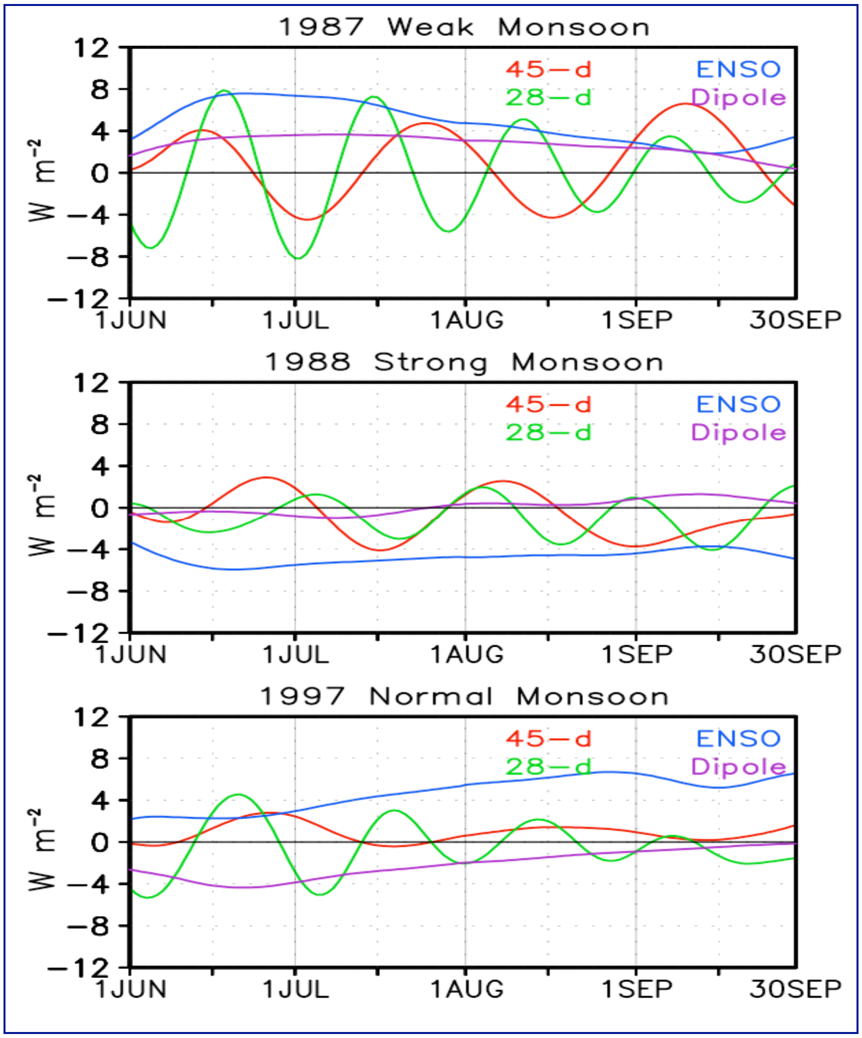

***Figure 2.4.2**: All-India averages reconstructed components obtained from MSSA of daily OLR anomalies shown for JJAS of 1987 (weak monsoon year), 1988 (strong monsoon year) and 1997 (normal monsoon year).*

The low level horizontal winds (from NCEP reanalysis) display similar 45-day and 28-day oscillatory patterns and the persisting ENSO and dipole patterns. A combined EOF analysis of horizontal winds at lower and upper levels has shown the existence of a strong seasonal signature throughout the season and nearly indistinguishable differences in the intraseasonal variability during strong, normal and weak monsoon years (Straus and Krishnamurthy 2006).

As a participant in the Monsoon GCM Intercomparison Project initiated by the CLIVAR Asian-Australian Monsoon Panel, monsoon simulations made with the COLA atmospheric GCM forced by observed SST were compared with those of nine other AGCMs (Kang et al. 2002a, 2002b, Waliser et al. 2003). The regional structures of the climatological mean precipitation simulated by the models differ from those of the observations. All the models simulate excessive rainfall over certain parts of the Indian monsoon region (mainly over the Indian Ocean) while there may be deficient rainfall over the central and northern parts of India. The intraseasonal patterns of the models are less coherent and lack sufficient eastward propagation although they exhibit some form of northward propagation. These patterns also display an overall lack of variability over the Indian Ocean.

The simulation of the monsoon by the CFS, the operational coupled model for dynamical seasonal prediction, was examined by analyzing daily precipitation, OLR and low-level horizontal winds from a long run (Achuthavarier and Krishnamurthy 2006). The space-time analysis has revealed seasonally persistent large scale modes with ENSO and Indian Ocean dipole patterns and one oscillatory mode with a period centered at 30 days. The most dominant 45-day oscillation found in the observation seems to be missing in the model simulation. However, there is an indication that there may be an oscillatory pattern of a much longer period similar to the 45-day oscillation.

2.4.1.2 Relation Between the Monsoon and SST

While examining the relation between the Indian monsoon and the tropical SST, it was found from the observations that a significant fraction of the variability of the tropical Indian and Pacific Oceans consists of cold (warm) SST anomalies in the western Indian Ocean, warm (cold) anomalies in the eastern Indian and western Pacific Oceans, and cold (warm) anomalies in the eastern Pacific (Krishnamurthy and Kirtman 2002). This combined variability has a distinct annual march and is strongly related to the Indian monsoon while the Indian Ocean dipole structure develops during June to November. This study suggested that the ocean-atmosphere coupling may be crucial in simulating the monsoon variability.

The importance of ocean-atmosphere processes has been demonstrated in another study by comparing the simulations of a coupled model and an AGCM forced by SST (Wang et al. 2005). It was shown that AGCMs forced by observed SST are unable to properly simulate Asian-Pacific summer monsoon rainfall and the observed lag correlations between rainfall and SST. While a coupled ocean-atmosphere model may simulate a realistic SST-rainfall relation, the AGCM forced by the SST generated by the coupled model fails to simulate the proper relation. The coupled ocean-atmosphere processes are crucial in the monsoon regions where atmospheric feedback on SST is critical.

The relation between the observed intraseasonal oscillatory modes and seasonally persisting modes (discussed earlier) and the SST in the tropical Indian and Pacific Oceans has also been investigated (Krishnamurthy and Kirtman 2006). The persistent ENSO mode in the OLR is strongly correlated with the ENSO pattern in the SST with significant correlation with lead/lag up to three months and points toward the influence of SST on the monsoon rainfall. The daily correlation between the all-India average of the OLR ENSO mode and the NINO3 SST anomaly index is about 0.8 for a period of about 6 months with significant correlation during the pre-monsoon period also (Fig. 2.4.3a). The persistent dipole mode in the OLR is similarly correlated (at a value of 0.4) with the dipole mode SST anomaly index. The atmospheric persistent ENSO mode in the NCEP CFS simulation also shows significant daily correlation with the SST in the Indian and Pacific Oceans but with values lower than those in the observations (Achuthavarier and Krishnamurthy 2006).

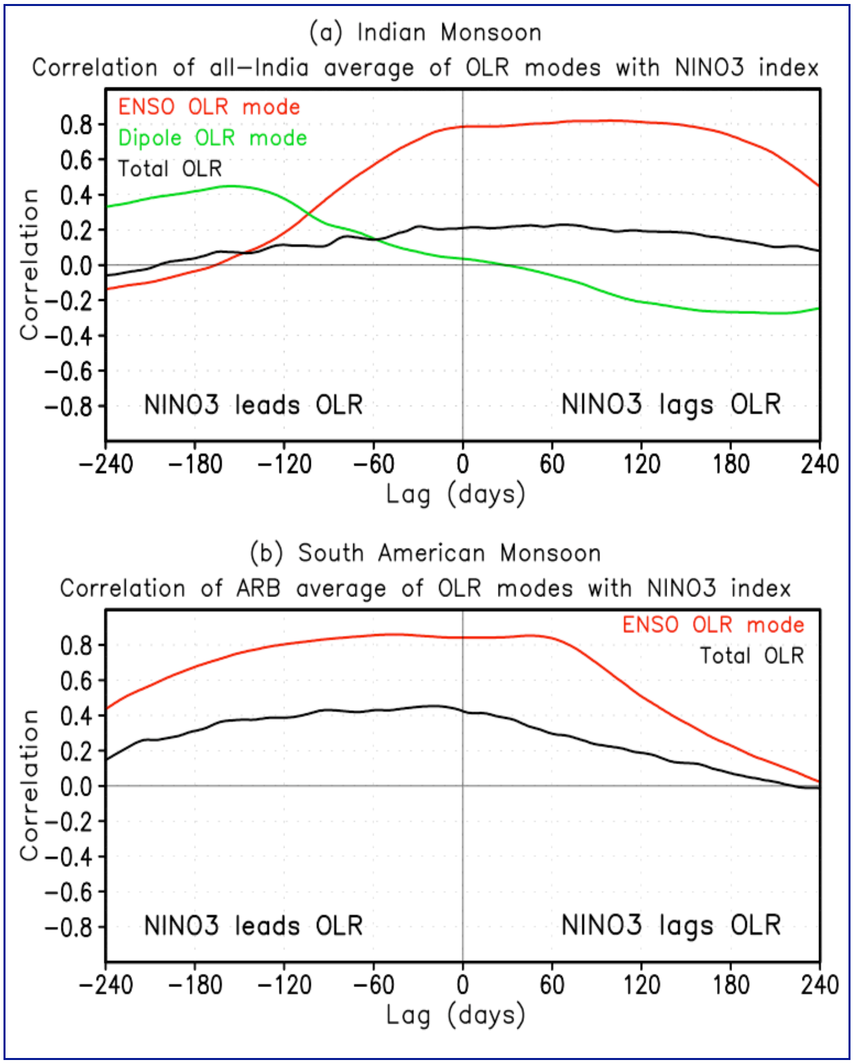

Figure 2.4.3: *Indian monsoon region: Lagged daily correlation between NINO3 SSTA index and all-India average of ENSO mode and dipole mode of OLR MSSA and total OLR anomalies and (b) South American monsoon region: Lagged daily correlation between NINO3 SSTA index and Amazon River Basin average of ENSO mode of OLR MSSA and total OLR anomalies.*

2.4.1.3 Statistical Prediction of the Seasonal Mean Monsoon

At present, the best predictions of Indian monsoon rainfall come from statistical prediction techniques. A major challenge in statistical prediction is finding the most efficient set of predictors out of a potential pool of thousands. DelSole and Shukla (2002) proposed a new criterion for selecting predictors and showed that this criterion often is superior to other selection criteria that have been proposed in the statistics literature. DelSole and Shukla (2002) applied this criterion to Indian monsoon rainfall prediction and showed that the predictive usefulness of indices based on El Niño, NAO, and the location of the 500hPa ridge over India, were dubious at best, a conclusion counter to prevailing opinion. This paper also raised several questions about the "power regression method," a method used by the Indian Meteorological Department to construct official forecasts of the monsoon. This paper has been cited frequently in Indian newspapers and was featured in *Science* and the *Bulletin of the American Meteorological Society*.

2.4.1.4 The Monsoon and Global Climate Variability

An updated review of the variability of the Indian monsoon on time scales ranging from subseasonal to decades and its relation to global climate variability was published as part of a book on global climate (Krishnamurthy and Kinter 2003). The mean monsoon and the annual cycle of rainfall over India, the intraseasonal variability, the active and break phases of rainfall and the interannual variability of rainfall were discussed in detail based on long records of daily rainfall data set created from observations at several thousand stations over India. The influence of SST in the Indian and Pacific Ocean, snow, land surface conditions and topography on the Indian monsoon from both observational and model studies were reviewed. The monsoon-ENSO relation on interannual and interdecadal time scales was discussed in detail using up-to-date data. The teleconnection to the NAO through the Eurasian snow cover and depth anomalies and the teleconnection to the African monsoon were also discussed. The progression of the statistical prediction of the seasonal mean monsoon rainfall performed by the India Meteorological Department was documented. In this regard, new results showing the interdecadal changes in the relation between the monsoon rainfall and the global climate parameters such as the NINO3 index, SLP at Darwin, the 500hPa ridge, the NAO index and the Eurasian surface temperature (some of which are used in the IMD prediction) were presented. The performance of atmospheric GCMs in simulating the monsoon and its variability were reviewed. The progress in the simulation of monsoon by the COLA AGCM models was also discussed.

2.4.2 South American Monsoon

2.4.2.1 Intraseasonal Variability of the South American Monsoon

While it has not received as much attention as the intraseasonal variability of the south Asian monsoon, there is considerable variability of the South American monsoon on intraseasonal time scales. Using the regional spectral model, Misra et al. (2002) showed that intraseasonal variability of the South American monsoon can be simulated by downscaling the NCEP reanalysis to a higher resolution horizontal grid. This result assumes significance in light of the fact that the OLR from the NCEP reanalysis rather poorly represents the intraseasonal variance over the South American monsoon region. It was also shown that there is a distinct diurnal variability of the intraseasonal variance of the South American monsoon, thereby suggesting the interplay of diurnal and intraseasonal variability (Misra 2004a). The predictability of the intraseasonal variability of the South American monsoon was demonstrated to be enhanced through diurnal rectification to the large-scale forcing from the lateral boundaries to the regional model (Misra 2005).

In a study applying MSSA to the observed OLR and reanalysis winds at upper levels over the South American monsoon region, it was found that the intraseasonal variability consists of a strong seasonally persistent mode and an oscillatory pattern with a period of about 55 days (Krishnamurthy and Misra 2006). The dominant persisting mode varies coherently with the Pacific SST on a daily time scale. The daily correlation between the NINO3 SST anomaly index and an index of the persisting mode averaged over the area of the Amazon River Basin is very high (Fig. 2.4.3b). The dominant persisting mode makes a significant contribution to the seasonal mean whereas the intraseasonal oscillation does not. The day-to-day variation depends on the relative roles of the persistent mode and the intraseasonal mode.

2.4.2.2 Interannual Variability of the South American Monsoon

Another predictability study of the South American monsoon with an AGCM forced with prescribed SST revealed that seasonal predictions consistently have more skill in precipitation variability than long-term (multi-year) integrations, indicating the debilitating role of the model drift (Misra 2004b).

The interannual variability of climate in subtropical South America is closely linked to the concomitant variability of the low level jet that modulates the moisture flux convergence. The variability of the low level jet along the leeward side of the Andes at interannual scales is dictated by the zonal movement/strength of the subtropical high in the south Atlantic Ocean (Misra 2002, 2003).

2.4.2.3 Nordeste Rainfall Variability

The co-variability of ENSO and the climate of the tropical Atlantic has been viewed through the robust interannual precipitation variability over the northeast Brazil (Nordeste). From AGCM studies, it was shown that the ENSO forcing of Nordeste rainfall is facilitated by the variability of the SST in the northern tropical Atlantic Ocean (Misra 2006). It was also shown that the intrinsic variability of the tropical Atlantic Ocean plays a critical role in the Nordeste rainfall variability and might act in ways that could diminish the influence of ENSO on the rainy season in that region.

Despite the claims made using forced AGCM sensitivity studies that northern tropical Atlantic SST anomalies are critical for the predictability of the Nordeste rainy season, Misra (2007) showed that ENSO continues to be the main source for Nordeste rainfall predictability. The study compared two versions of the COLA coupled model that had very different ENSO characteristics. The predictability of the teleconnection of the Nordeste rainy season variability to northern tropical Atlantic SST anomalies is a result of the influence of ENSO. He also argued that forced AGCM studies that test the sensitivity of Pacific SST variability are flawed by design, when they accommodate SST anomalies of the northern tropical Atlantic that could well be a manifestation of ENSO, while prescribing climatological SST over the Pacific Ocean.

3. LAND-CLIMATE INTERACTION

A long-standing pillar of COLA research has been investigation of the role of the land surface in controlling or modulating climate predictability. The hypothesis articulated by Charney and Shukla (1981) and tested in a global numerical experiment by Shukla and Mintz (1982) is that the modulating effect on the surface radiation budget by different land surface types and vegetation, and the slow processes associated with the movement of water through the land component of the hydrological cycle introduce time scales that are much longer than those normally linked to weather variability and can therefore enhance predictability. COLA research has had a goal of testing this hypothesis and quantifying the effects of the land surface. In the breakthrough GLACE experiment, it was shown that the sensitivity of seasonal climate predictability to variations in the land surface conditions is highly variable, both in location and from year to year, with the most highly sensitive locations in the transition regions between wet and dry climate zones. Because this and related results on land-atmosphere interaction depend heavily on the land surface model, and because land surface modeling is a relatively new area of inquiry, COLA research includes active development of the land surface model. Similarly, because there is a dearth of observational data to validate land surface models and verify results on land-atmosphere interaction, COLA scientists have been at the forefront of the development of new global soil wetness and surface flux data sets.

3.1 Coupled Land-Atmosphere Sensitivity

3.1.1 Land-Atmosphere Seasonal Predictability

Coupled land-atmosphere models, like coupled ocean-atmosphere models, easily drift away from observed realistic states. This occurs because the coupled system naturally strives to achieve a state of equilibrium. If fluxes of heat and moisture between surface and atmosphere are not the same as observed, the point of balance in the models will differ from reality, and the reservoir terms (manifest in soil moisture, surface temperature and near-surface humidity) and response fluxes (such as precipitation) will also deviate from observations. Some component of the trends over land can come from remote sources (Zhao and Dirmeyer 2004), but the local drift in equilibrium state, typically towards extremes, desensitizes the model to respond to realistic anomalies in intial conditions (Dirmeyer 2003). Land surface states do influence the atmosphere significantly (e.g., Reale and Dirmeyer 2002; Reale et al. 2002), but the influence of land surface initial conditions on predictability is minimal without some form of correction to the downward fluxes of energy and water over land to remove systematic errors (Dirmeyer and Zhao 2004).

When correct interannual variability is specified in the atmospheric fluxes, the land surface is capable of transmitting that information back to the atmosphere – the degree to which this occurs is a measure of the land surface's role in climate feedbacks and predictability (Dirmeyer 2005, Zhao et al. 2006). Figure 3.1.1 shows what happens to the GCM simulation of boreal summer precipitation when the erroneous model fluxes are replaced with the observed. Dark bars show the spatial correlation coefficient over North America for the control ensemble where realistic atmosphere and land surface initial conditions and global SST are specified, but the atmosphere runs freely. The hatched bars are for an identical ensemble where observed fluxes of rainfall are fed to the land surface scheme in place of the model fluxes. One, two and three stars denote significant differences between the two cases at 90%, 95%, and 99% confidence levels, respectively. The impact that correct water fluxes to the land surface have on climate through the pathway from land to atmosphere is positive in every year, and generally significant. The pathway through which signal (and errors) propagate through the coupled land-atmosphere system is not a simple water cycle pathway, but a complex path through both water and energy cycles, circulation and physical processes (Dirmeyer 2006).

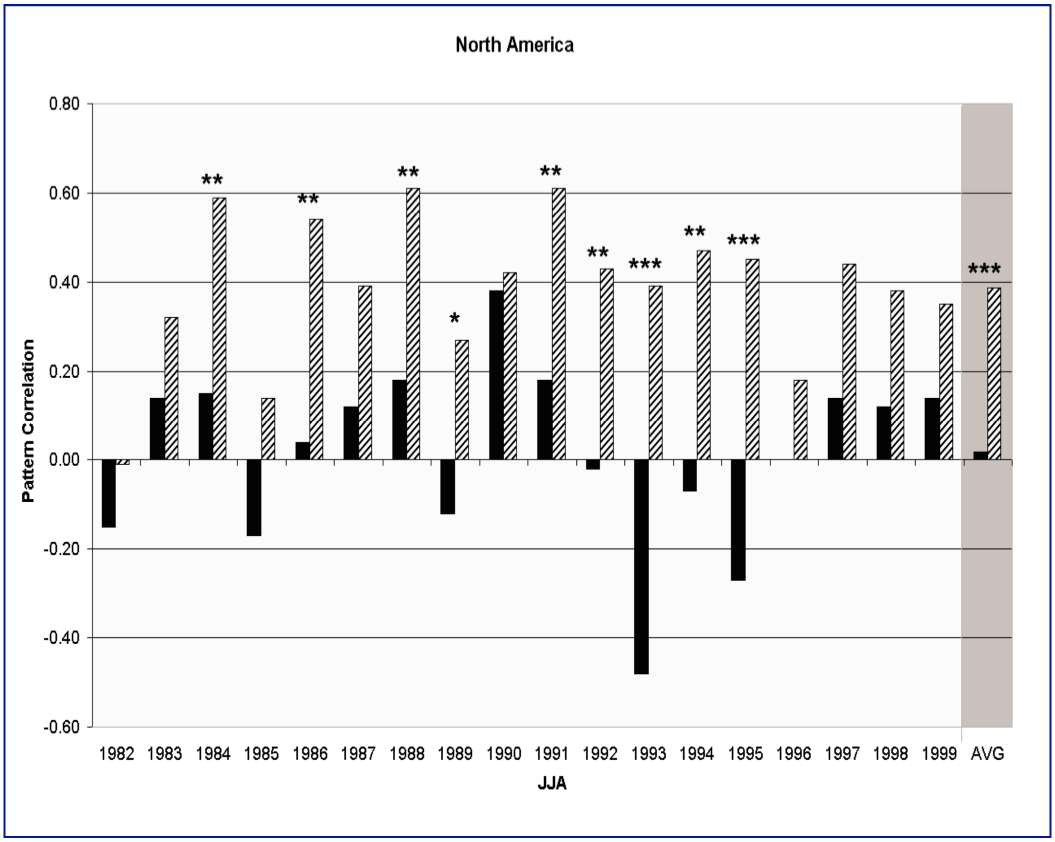

***Figure 3.1.1**: Seasonal SACC precipitation in cases LIC (solid) and P (hatched) for each year, and in the last column (shaded) the mean of the 18 years. Asterisks denote statistical significance (from Dirmeyer 2005).*

3.1.2 Land-Atmosphere Coupling Strength

It has long been understood that the land surface has an influence over weather and climate just as the ocean does. However, these conclusions have been based principally on large-scale modeling studies. Each individual result, therefore, is dependent on the properties of the model used, which may or may not represent the behavior of the real world with adequate fidelity. The question remained open – how strongly are the land and atmosphere coupled in terms of climate feedbacks in the various global models? A preliminary study (Koster et al. 2002) with four models suggested there was a wide range of variability among models in the degree to which soil moisture could modulate the evolution of precipitation. Also, spatial patterns of "coupling strength" varied greatly between models.

This prompted a larger controlled study that established for the first time a consensus estimate of the global patterns of land-atmosphere coupling strength (Koster et al. 2004). "Hot spots" of coupling strength during boreal summer were identified over the Great Plains of North America, the Sahel of Africa, and regions of South and East Asia (Koster et al. 2006).

Careful comparison of the output from the 12 models in GLACE showed that coupling strength varies greatly among the world's state-of-the-art general circulation models (Guo et al. 2006). Additionally, the strength can be broken down into contributions from the land surface model (the link between soil moisture and evapotranspiration) and the atmospheric boundary layer and precipitation parameterizations (linking evapotranspiration to precipitation).

Few locations exist where the necessary subsurface, surface and boundary layer measurements of state variables and fluxes have been taken to validate these models. Do the models exhibit the observed relationships among land and atmosphere variables? Dirmeyer et al. (2006) found that at the few locations where sufficient collocated observations exist, individual models rarely exhibit the proper relationships between surface fluxes and state variables. Yet the multi-model average usually has the best characteristics.

3.2 Water Cycle Predictability

3.2.1 Soil Wetness Data Comparison

Motivated by the need for land surface initial conditions that are consistent across many models (for purposes of initializing multi-model experiments), Dirmeyer et al. (2004) conducted a comparison of eight long-term global gridded soil wetness products (six produced by models and two from remote sensing). Spatially dependent degrees of correlation exist among the products, suggesting there may be some benefit to combining products to create an ensemble soil wetness product. Validation with in situ data from many sites around the world showed varying degrees of correlation in simulating the annual cycle and anomalies.

Gao and Dirmeyer (2006) found that statistical corrections can be developed and applied to improve model time series of soil moisture from reanalyses or offline simulations. These corrections are trained on observed soil wetness data. However, they are not transferable from model to model or location to location. This implies that there is little hope of calibrating corrections over a data rich region and then applying the corrections elsewhere, even where the vegetation and climate are similar.

3.2.2 Global Land Surface Climatology

Global data sets for parameter specification, meteorological forcing, and validation were produced for use in the Second Global Soil Wetness Project or GSWP-2 (Zhao and Dirmeyer 2003). The data sets are based on the International Satellite Land-Surface Climatology Project (ISLSCP) Initiative II data, but many of the fields represent additional processing, such as the production of "hybrid" data sets combining gridded observations (low temporal resolution) with model reanalysis (high time resolution). This hybridization removes systematic errors in the reanalysis data (Betts et al. 2006), providing a superior set of forcing data for the land surface models.

Over a dozen land surface models participated in GSWP-2. Comparison of the models' simulation of soil wetness where long-term observations exist confirmed that models have different operating ranges of soil wetness, and thus mean errors may very greatly. However, when the mean annual cycle of each model is removed, the models perform very similarly to one another when the forcing data are the same (Guo and Dirmeyer 2006). Nevertheless, the models generally outperform previous gridded estimates from reanalyses and single-model offline calculations (Guo et al. 2006a). The multi-model mean performs best of all in nearly every region of the globe and by every measure. The multi-model product was constructed with careful quality and error checking of the individual model fields, and has been distributed on DVD as a GEWEX data product (Dirmeyer et al. 2006).

A number of sensitivity studies were also performed with many of the participating models. Forcing and parameter data sets were changed to assess the impact of uncertainty in key meteorological parameters (e.g., precipitation, radiation and near surface meteorology) exemplified by the different global observationally-based products and reanalyses available. Guo et al. (2006b) found that the choice of forcing data had clear impacts on the simulation of soil wetness. Hybridization of reanalysis products with observed data substantially improves the simulation of soil moisture. The greatest sensitivity was to the choice of precipitation. The range of skill for one model across 13 different combinations of forcing data were as large as the range across a similar number of land models using the same forcing (Fig. 3.2.1).

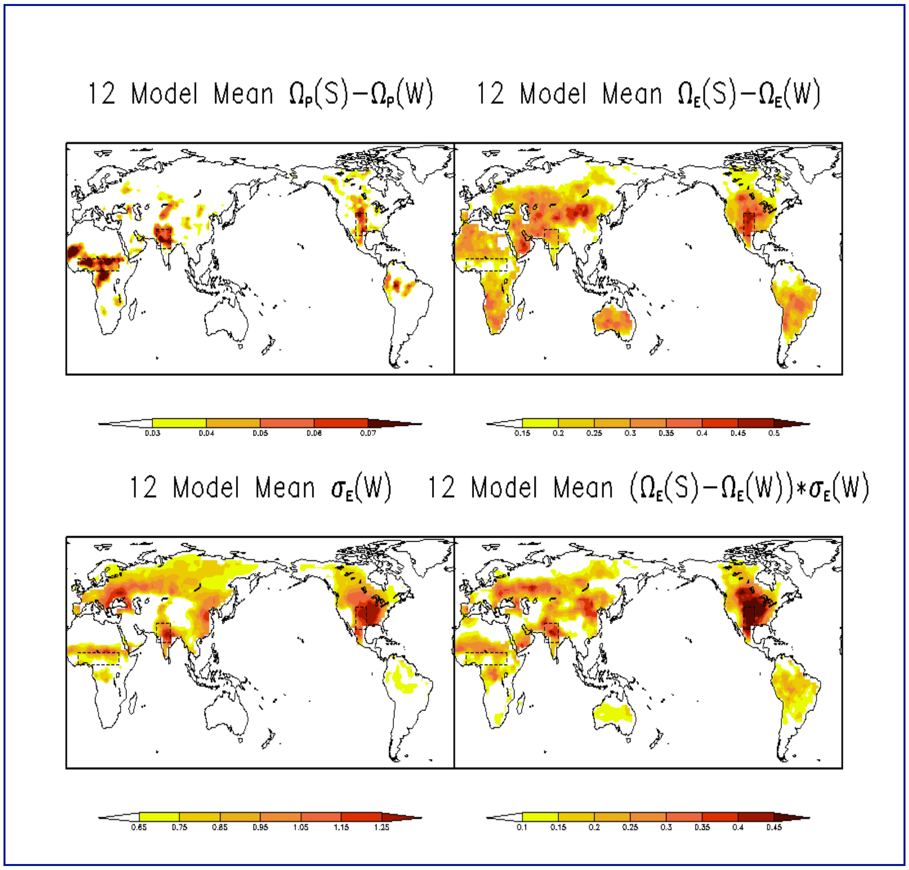

***Figure 3.2.1**: Average of coupling strengths measured by changes in a) precipitation similarity among ensemble members where soil moisture is specified identically; b) evapotranspiration (ET) similarity; c) standard deviation of ET; and d) the product of b) and c) across all twelve models (from Guo et al. 2006).*

The GSWP-2 data have also been used as the basis for development of a version of the L-MEB microwave brightness temperature model that can be driven by any land surface model (Gao et al. 2004). This forward modeling approach is used to estimate microwave brightness temperatures as would be observed by space-based large-footprint satellites, and includes the contaminating effects of dense vegetation on the signal.

The GSWP-2 multi-model analysis has also been used to estimate soil moisture memory as a function of space and time (Fig. 3.2.2). These results compare favorably with multi-model GCM estimates from the GLACE simulations for boreal summer (Seneviratne et al. 2006).

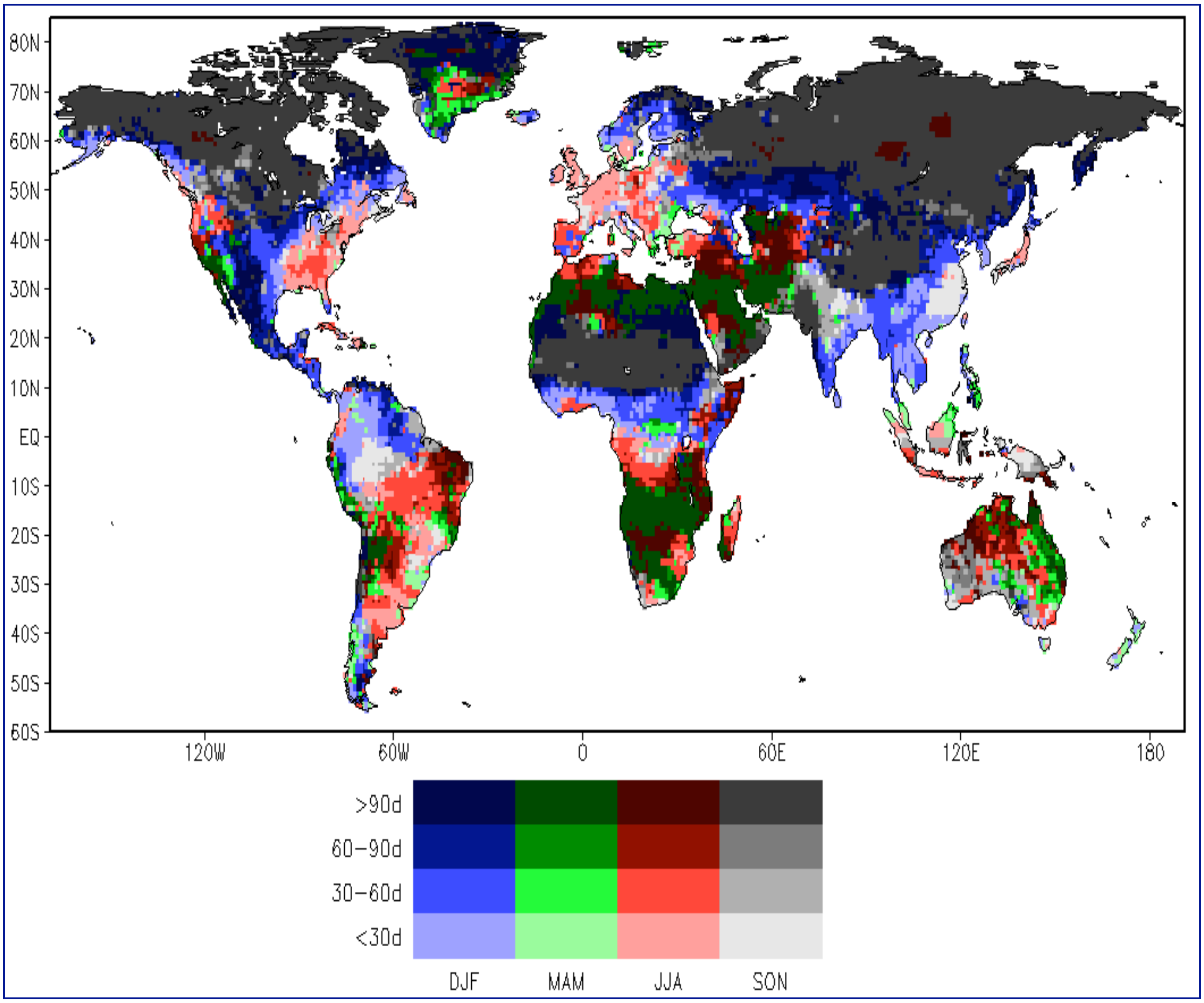

Figure 3.2.2*: Season and duration of maximum soil moisture memory from the GSWP-2 multi-model analysis*

3.2.3 Atmospheric Water Transport

25 years of back-trajectory calculations from 4,257 land points (T62 NCEP reanalysis grid, excluding Antarctica) have been completed and compiled into monthly increments. A global climatology of precipitation recycling has been compiled from these calculations (Dirmeyer and Brubaker 2006a). The method allows scaling by area, so that different regions can be compared by normalizing to a common reference area. For a spatial scale of 10^5 km^2, the global mean recycling ratio for land areas is 4.5%, but there is much spatial and temporal variability. High altitude regions have some of the highest recycling ratios, while high latitude regions have large annual cycles. Positive trends are seen in many high-latitude areas, particularly during spring (Dirmeyer and Brubaker 2006b). This suggests a lengthening of

hydrologic summer in many of the same areas that are experiencing the most pronounced warming trends and lengthening of the growing season (Fig. 3.2.3).

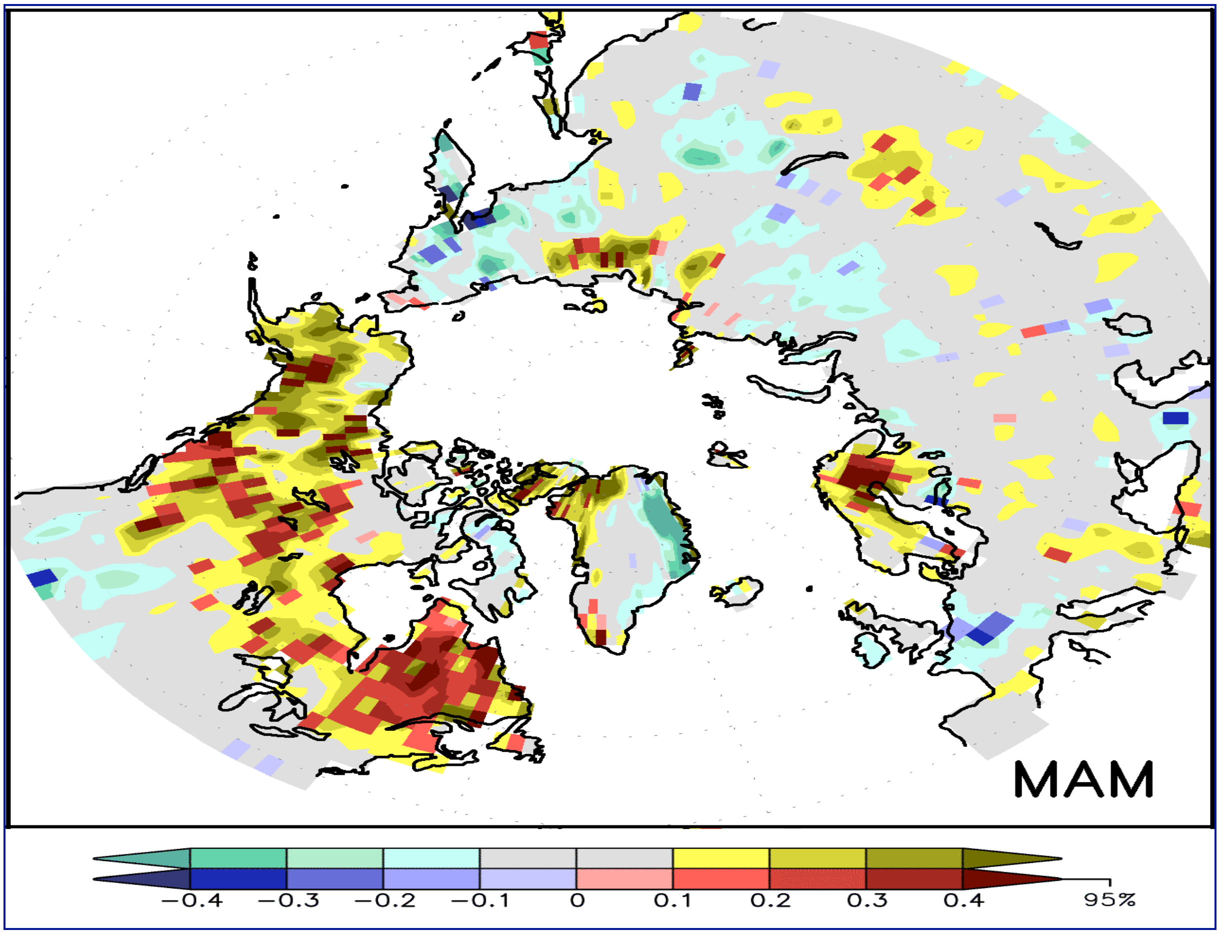

***Figure 3.2.3**: Trend in the recycling ratio (percent per year during 1979-2003) during boreal spring scaled to a common reference area of 10^5 km^2. Trends significant at the 98% confidence limit are shown in shades of red (positive) and blue (negative), 93% in yellow (positive) and green (negative).*

3.3 Vegetation Variability and Climate Predictability

Among the sensitivity tests in GSWP-2 was one in which the specified interannually varying vegetation properties (greenness and coverage) were replaced with a mean annual cycle. Gao et al. (2006) found some sensitivity of surface latent heat fluxes, but the offline simulations were highly constrained by prescribed surface radiation, precipitation and meteorology. When similar 10-year simulations with a coupled land-atmosphere climate model were conducted, the feedbacks amplify sensitivities clearly in some cases and regions. For instance, Fig. 3.3.1 shows the impact of realistic versus climatological vegetation on simulation of the 1993 floods over the northern Great Plains. The floods are only simulated during May and June when the realistic vegetation is prescribed. During July there appears to be no effect. With a limited ensemble size of 10, often the differences between cases when regional vegetation anomalies were large are not significant, and in other cases there is no discernable impact at all. It is difficult to say that a failure to simulate a change means vegetation is not important, but cases of significant response suggest that vegetation phenology may play an important role in climate anomalies in some situations.

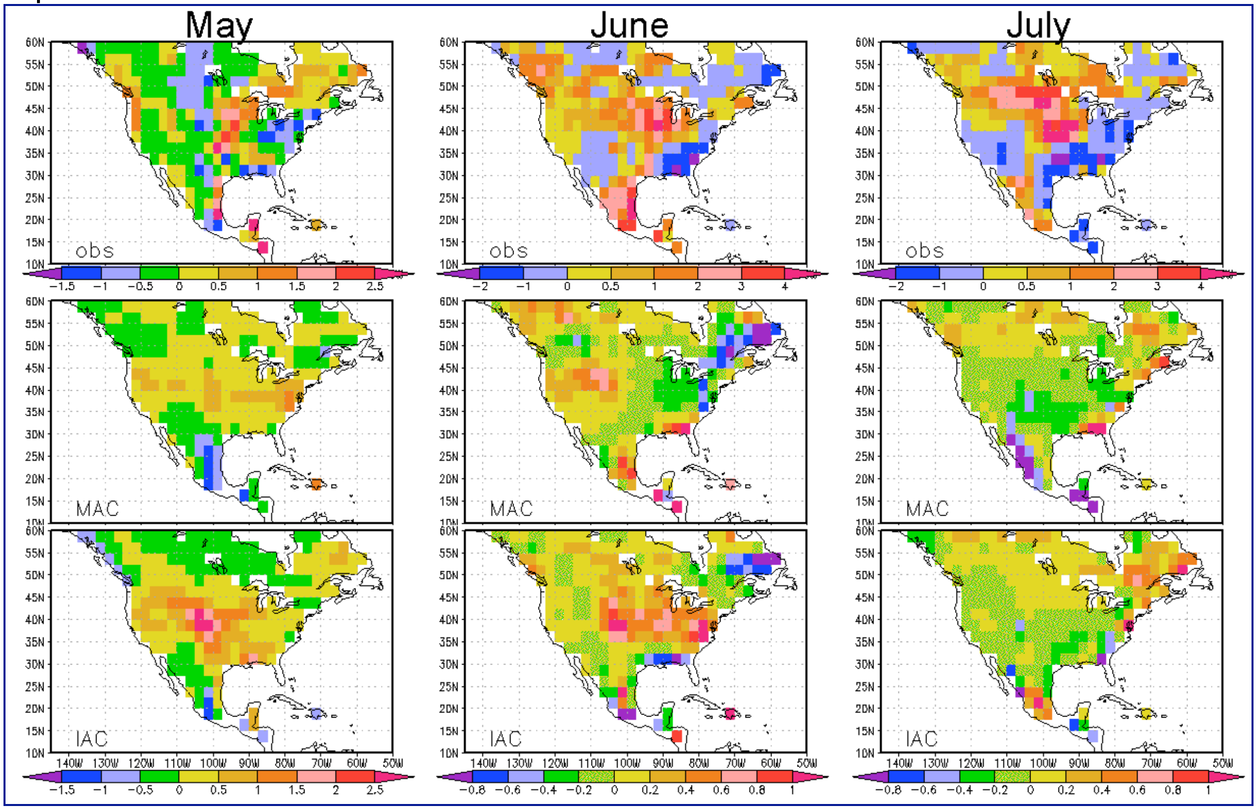

Figure 3.3.1: *Precipitation anomalies (mm/d) for the given months of 1993 as observed (top row), in a climate model with climatological vegetation (middle) and with realistic vegetation based on ISLSCP data (bottom row).*

3.4 Land Model Development

The latest version of the COLA land surface scheme has been incorporated into the COLA AGCM for Version 3. It includes a 6-layer soil model with 4 layers in the root zone (reducing errors in surface temperature and "stomatal suicide" in evapotranspiration), improved runoff parameterization and river routing (for hydrologic validation and supplying fresh water to an OGCM). This version was used for GSWP-2 has been run offline for over 40 years at T62 resolution with observationally-based forcing from ERA-40 and gridded observed precipitation to provide land surface initial conditions for COLA GCM integrations.

COLA participated in the initial development of the Community Land Model (CLM; Dai et al. 2003, Oleson et al. 2004) before maintenance was handed over to NCAR personnel. COLA also collaborated in the development of the Land Information System (LIS; Kumar et al. 2006), a framework for high-performance high-resolution multi-model integration and data assimilation that won the 2005 NASA Software of the Year Award.

4. SEASONAL TO DECADAL PREDICTABILITY IN A CHANGING CLIMATE

4.1 Climate of the 20th Century

4.1.1 Relationship of Climate Trends and Northern Hemisphere Circulation Regimes

While a great deal of attention has been paid to the projection of recent climate trends on the Arctic Oscillation (AO) (often also called the Northern Hemisphere annular mode or NAM; Thompson and Wallace, 1991), much less attention has been paid to the component of the trend that is congruous with the Cold Ocean-Warm Land (COWL) pattern (Wallace et al., 1995). This latter pattern is thought to contain the indirect component of climate change, i.e. that component mediated by the circulation.

Wu and Straus (2004) examined the trends in the wintertime (Jan.-Mar.) seasonal means of a large number of fields, and undertook a careful analysis of how the trends projected only the leading modes (AO and COWL), and the sensitivity of the results to choices of definition. The fields examined included SLP, surface air temperature, geopotential height at 500 and 50 hPa, temperature at 500 and 50 hPa, and zonally averaged fields of height, temperature, horizontal winds and vertical motion in the domain 1000-50 hPa, 20°N-90°N. The data were obtained from the NCEP/NCAR reanalysis for the 55-year period of 1948-2002. In each case, the trend fields are expressed in terms of two alternative expansions: (i) contributions from the AO and COWL patterns, which are defined as the leading EOFs of sea-level pressure; or (ii) contributions from the modified AO (called the AO*) and modified COWL (COWL*) patterns, defined from the leading EOFs of 500 hPa height. The completeness properties of the expansions were studied, and the residuals in the expansions considered.

The long-term linear trends of the fields at mid- and lower-tropospheric levels project well on to the AO (AO*) and COWL (COWL*) modes. The AO contribution accounts for most of the SLP falls over the Arctic and half of the sea level pressure rise over the North Atlantic, while the COWL pattern represents the entire negative pressure trend over the Pacific and half of the rise over the Atlantic. In the expansion into AO* and COWL* components, the latter represents most of the SLP trend.

The observed surface air temperature trend (warming over most of North America and Asia, cooling over northeast Canada and the Pacific) is partitioned nearly equally between contributions from the AO and COWL, although the COWL contribution dominates over North America. In the alternative expansion, the COWL* dominates nearly all the warming over North America and Asia. The mid-tropospheric (500 hPa) temperature trend is mostly due to the COWL (or COWL*) patterns, with the AO representing only the local cooling over Greenland.

4.1.2 Trends in the NAO

Several studies have suggested that observed trends in the wintertime North Atlantic Oscillation are related to forcing by increasing greenhouse gases. We investigated this issue using integrations conducted with the COLA V2 AGCM, as part of the Climate of the 20th Century (C20C) experiment, and came to different conclusion from that which had been obtained by others. The experiments and results are described in Schneider et al. (2003).

The impact of observed global SST trends during the second half of the 20th century on the Northern Hemisphere extratropical winter atmospheric circulation was investigated using ensembles of simulations with the COLA atmospheric GCM forced by the observed SST evolution. In contrast to some other studies, the simulated ensemble mean 500 hPa trends in the North Atlantic sector do not resemble the observed trend (Fig. 4.1.1). However the intra-ensemble variability of the trends is large, with the dominant structure of that variability resembling the Arctic Oscillation or NAM. Comparing T21, T42, and T63 ensembles, the model results do not depend strongly on horizontal resolution, although there may be dependence on the model physics.

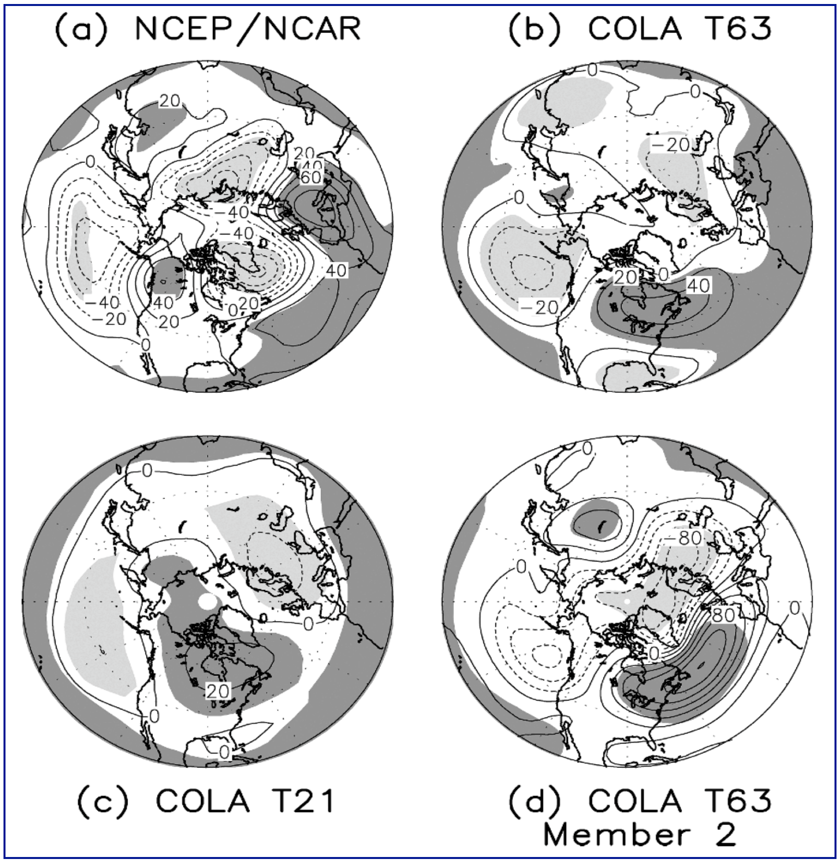

Figure 4.1.1*: Linear trend of the 500 hPa DJF geopotential height of (a) the 1948~1999 NCEP/NCAR reanalysis data, (b) trend of the mean of a 10 member ensemble of integrations with a T63 version of the COLA AGCM forced by observed 1948-1999 SST, (c) as (b) for a T21 ensemble, (d) a particular member of the T63 ensemble. The contour interval is 20 m (50 years)$^{-1}$.*

The model results are consistent with the interpretation that the observed trend is dominated by the forced signal in the Pacific/North America sector, while over the rest of the Northern Hemisphere, and especially in the North Atlantic sector, the trend is primarily inter-decadal internal atmospheric noise with an annular structure.

In order to diagnose the origins of the forced component of the model trend, a series of equilibrium response simulations was performed using constant-in-time SST anomalies with the structure of the trend superimposed on the annually varying climatological SST. It was found that the SST trend in the latitude belt from 20°S to 20°N is responsible for forcing much of the extratropical trend, and that the dominant tropical forcing is the SST trend in the Indian Ocean/west Pacific and eastern Pacific sectors.

The idealized experiments show that the precipitation response in the tropics is linearly related to the SST trend, and that the NH DJF height response to SST anomalies in various regions is quasi-linear.

Some additional analysis and interpretation was given. The extratropical response to low latitude SST trends in the idealized experiments has characteristics reminiscent of Rossby wave trains forced by tropical deep convection. The intra-ensemble variability in the model's extratropical zonal mean height trend, which cannot be explained by external forcing, appears to be due to variability in the trends of midlatitude eddy stirring. The observed zonal mean trend also shows evidence of forcing by trends in the eddy stirring.

4.1.3 Role of Noise and Coupled Feedbacks in North Atlantic SST Variability

We used a state of the art coupled GCM forced by NCEP/NCAR reanalysis to diagnose the mechanisms that cause the observed low frequency variability of SST in the North Atlantic. The GCM simulations are part of the thesis work of a GMU student (Meizhu Fan) and will be submitted for publication in due course.

There are four elements of our experimental procedure:

1) Diagnose the "forced" surface fluxes as the evolution of the ensemble mean atmospheric surface fluxes from an ensemble of AGCM simulations forced by the observed SST evolution.
2) Determine the fluxes associated with "unforced weather noise" by subtracting the forced fluxes from the reanalysis fluxes.
3) Force the interactive ensemble anomaly coupled GCM with the atmospheric weather noise.
4) Diagnose the mechanisms causing the response in the control runs by selectively coupling/decoupling the ocean and atmosphere by region and process.

The interactive ensemble coupled GCM, currently unique to COLA, filters out the unpredictable oceanic noise and atmospheric weather noise simulated by the atmospheric component from the surface forcing of the ocean in the coupled GCM, leaving a coupled GCM in which that part of the noise forcing can be *specified* and controlled exactly. In this way, we combine the virtues of the simple model studies (control of noise and coupled process) with the virtues of experiments made with more realistic models (realistic forcing structures; comparison of simulated and observed evolution and consequent implications for understanding of nature and for model verification).

The model used was the anomaly coupled GCM, described by Kirtman et al. (2002). The atmospheric component was version 2 of the COLA AGCM with T42 horizontal resolution and 18 levels in the vertical. The ocean model was the GFDL MOM3 with 1.5° horizontal resolution (meridional resolution increasing to 0.5° in the tropics) and 25 levels in the vertical. The interactive coupled ensemble technique (Kirtman and Shukla, 2002) was used. In this technique, multiple copies (in our case six) of the AGCM were coupled to a single copy or multiple copies (in our case six) of the OGCM. Each atmospheric (oceanic) model was forced by the mean SST (surface fluxes) from the ocean (atmospheric) models which was updated daily. However, the atmospheric (oceanic) models were started with slightly different initial states. Due to the chaotic nature of atmospheric (oceanic) dynamics, the "weather" in each copy of the atmospheric model and the daily evolution in each copy of the oceanic model can be viewed as noise independent of that in the other atmospheric (oceanic) models. The ensemble was interactive in that the ensemble mean surface fluxes over all copies of the atmosphere and ensemble mean SST over all copies of the ocean were then used to force the ocean (atmosphere) model, determining the SST (surface fluxes) evolution. Therefore, the interactive coupled ensemble filters out the atmospheric weather noise forcing of the ocean (oceanic forcing of the atmosphere due to oceanic internal variability) but preserves the coupled atmosphere-ocean feedbacks. Since transient eddies are realistically represented in each copy of the AGCM (OGCM), the interactive coupled ensemble also realistically represents the interaction between atmosphere and the ocean.

The starting point for this investigation was to estimate the atmospheric weather noise of the surface fluxes in the atmospheric reanalysis and oceanic noise of SST in the oceanic reanalysis. To do this, we subtracted from the atmospheric reanalysis the surface fluxes that are forced by the observed 1951-2001 SST evolution. Each member of the ensemble produces a solution that consists of the forced solution plus atmospheric weather (oceanic) noise, and ensemble averaging eliminates the noise in the surface fluxes (SST).

The diagnosed evolution of the 1951-2001 atmospheric weather noise surface fluxes of the North Atlantic was used to force the interactive ensemble in a single 50-year simulation. The results (Fig. 4.1.2) indicate that the interannual-to-decadal SST variability in the North Atlantic is forced by the noise (e.g. the NAO), and that the NAO itself is noise and not the response to the SST. The results also indicate that there is a significant response of the tropical Atlantic SST to the extratropical noise forcing.

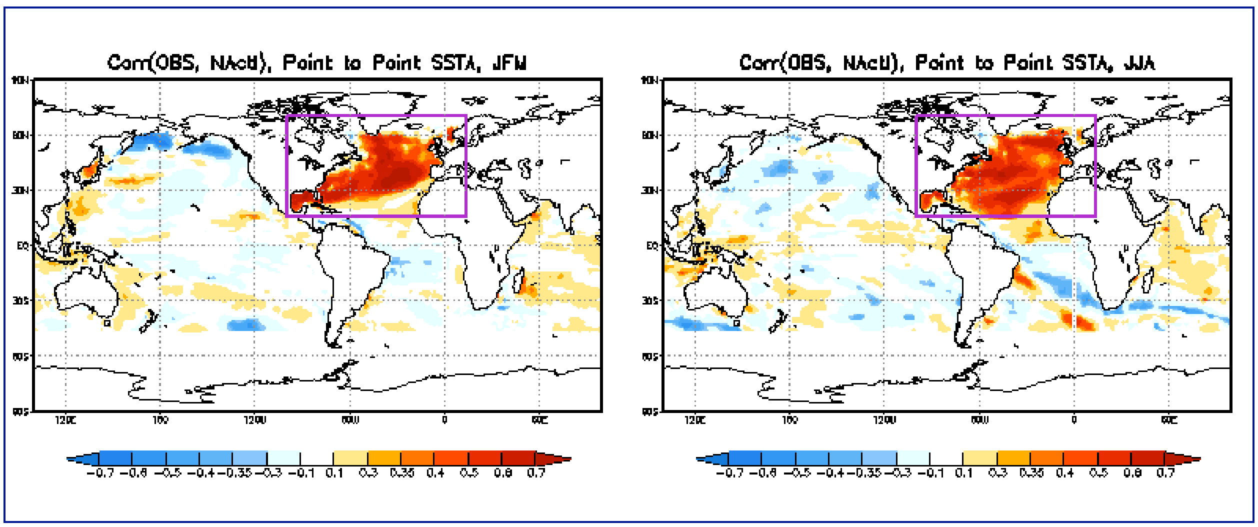

***Figure 4.1.2**: Point correlation of SST 1951-2000, simulated with observed, from interactive ensemble CGCM experiment where the ocean inside the purple box (15-65°N) is forced by weather noise derived from NCEP/NCAR reanalysis surface fluxes, no weather noise forcing outside the box. Left: JFM means. Right: JJA means.*

A theoretical analysis of the interactive ensemble approach in the context of the simple Barsugli and Battisti (1998) model is described in Schneider (2006). There, it was shown how to take the influence of land and sea ice account to correctly calculate the noise forcing. Additionally, it was shown that it is necessary for both the reanalysis and the diagnostic model to include the external forcing in order to evaluate the noise correctly. A practical application was made by comparing the response of the simple interactive ensemble model to noise forcing obtained from the NCEP/NCAR and ERA40 reanalyses. Prominent differences were found, and there is some indication of serious errors in the NCEP/NCAR reanalysis over land.

4.1.4 Pacemaker Experiments

Recently, several studies have suggested that important elements of atmosphere-ocean co-variability cannot be reproduced when the atmosphere is forced to respond passively to the prescribed SST (e.g. Wang et al. 2005). To mimic the important aspects of this air-sea coupling while maintaining the ability to simulate the observed climate of the 20th century, "pacemaker" experiments, in which the tropical Pacific SST is prescribed from observations but coupled air-sea feedbacks are maintained in the other ocean basins (e.g. Lau and Nath, 2003). In this framework, the SST is prescribed in a limited region only (for example, the NINO3.4 region). Outside of the prescribed region we use a mixed-layer ocean model. We have adopted this methodology primarily for two reasons. If the model is forced with prescribed SST at all points, then the energy balance at the surface is inconsistent. This can have a dramatic influence, for example on the simulation of the monsoon. Coupling a AGCM to a mixed-layer ocean outside of the pacemaker region ensures a consistent surface energy budget and improves the accuracy of the simulation of the monsoon compared to a model with fully prescribed SST. The second reason for adopting this methodology is that we want the model results to be directly comparable to the climate record. Because a fully coupled model initialized with an observed oceanic state quickly drifts away from the observed evolution, such a model cannot be used if the precise time series of observed climatic events is to be simulated. By prescribing SST in the tropical Pacific, we ensure that the observed sequence of this critical forcing is present in our simulations with the observed timing and amplitude.

4.1.4.1 Experiments with COLA CGCM

The model used in this portion of the study is the COLA AGCM v3.1, which is an update of the AGCM described in Schneider (2002), and closely related to the COLA v3.2 model described in Misra et al. (2006). The model has 28 vertical levels and is run at T62 resolution. The world ocean is separated into two domains. In one domain, including the tropical eastern Pacific and the polar regions, we prescribe SST taken from the HadISST1 data set. In the other domain outside the prescribed SST regions, we use a 50 m slab mixed-layer model to represent the ocean. A 5-point transition zone is also used in which the prescribed and modeled SST are blended before being used by the AGCM as a lower boundary condition. Each experiment consists of an eight-member ensemble integrated for the period 1950-2002.

The composite model DJF SST anomalies (Fig. 4.1.3) have significant amplitude not only in the prescribed region in the eastern Pacific but also in widely separated regions around the globe. There are clear negative anomalies in the horseshoe region in January (Fig. 4.1.3b) and February (Fig. 4.1.3c). Although these anomalies are weaker than observed (compare to Fig. 4.1.4), examination of the composite anomaly fields for individual ensemble members (not shown) indicates that this is due in part to averaging over the eight members of the ensemble. The model composite anomaly fields are also more similar to each other than to the observed fields (compare to Figs. 4.1.3a-c), where there are notable differences between months outside of the tropical Pacific. The fact that the composite SST anomalies have significant amplitude outside the central and eastern tropical Pacific indicates that, to a certain extent, SST anomalies in these regions during ENSO years can be considered a response to the forcing in the eastern tropical Pacific. Given the lack of ocean dynamics and the fact that the model is relaxed towards climatology and not the observed record of SST, the close correspondence between the model and observed anomaly patterns is very encouraging.

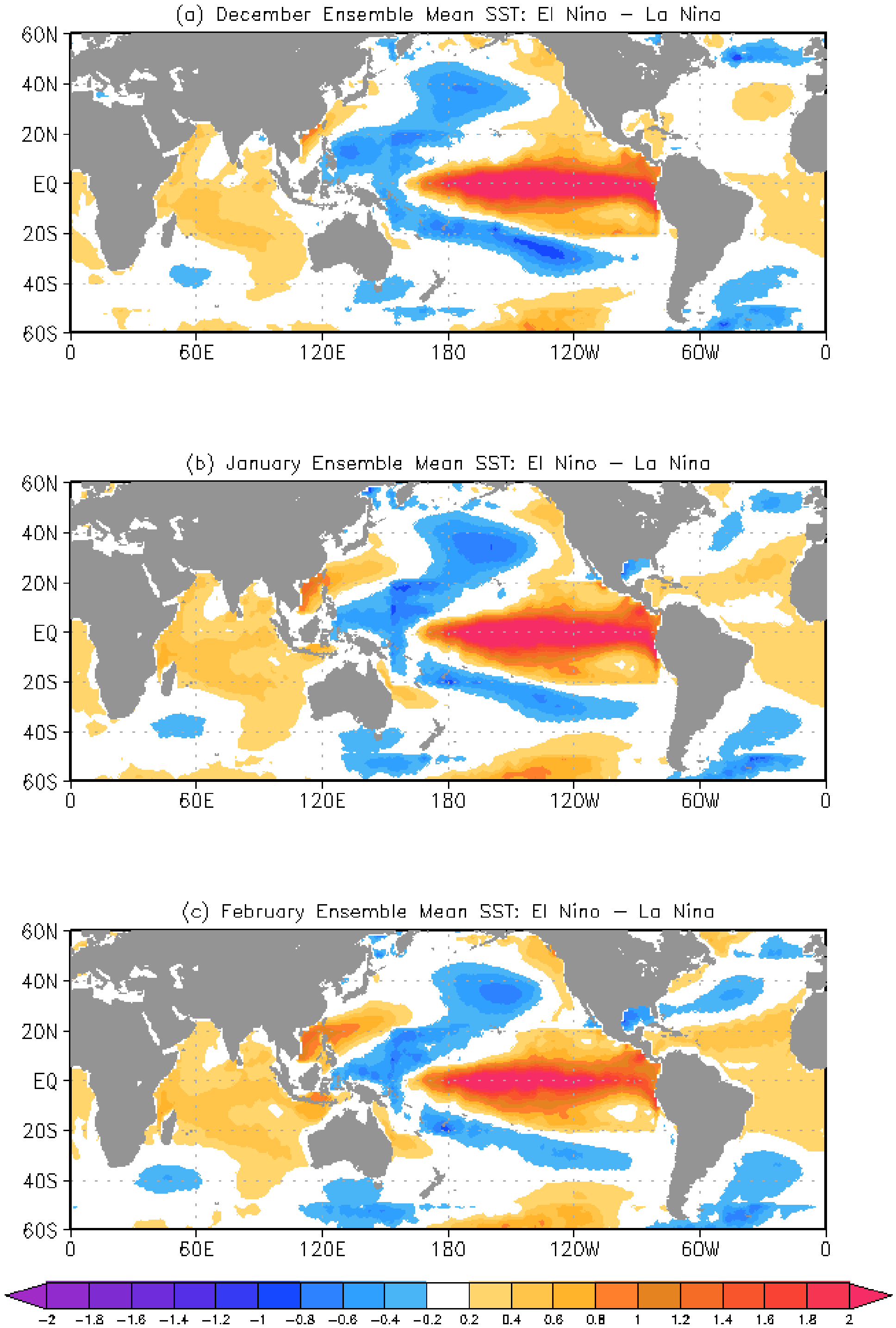

Figure 4.1.3*: Model ensemble mean SST difference for warm-cold ENSO events for a December, b January and c February. Warm and cold events are based on CPC DJF Niño3.4 index*

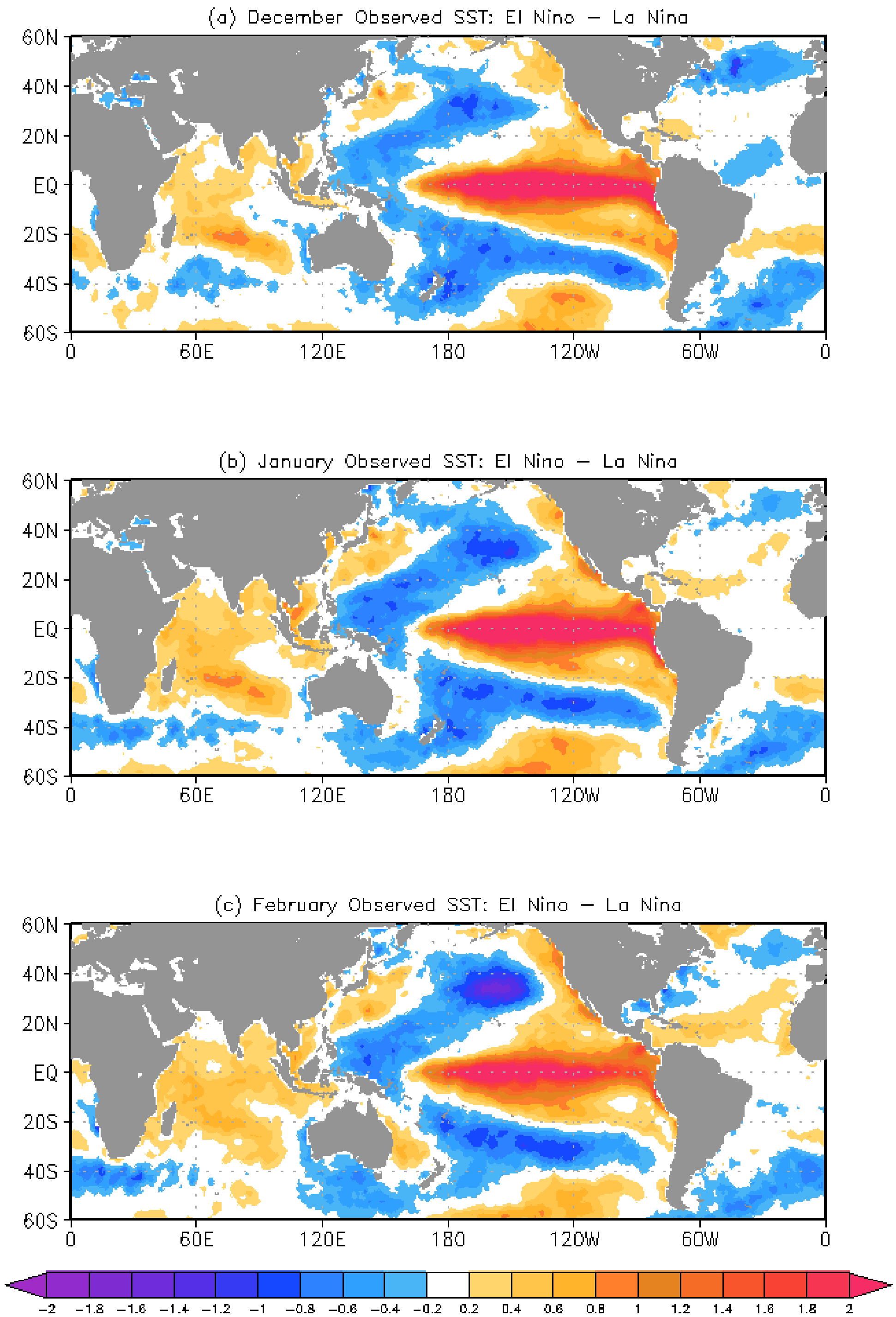

***Figure 4.1.4**: Observed SST difference for warm-cold ENSO events for a December, b January and c February events are based on CPC DJF Niño3.4 index..*

One interesting application of this methodology is to improve the model simulation of the south Asian monsoon, which is notoriously difficult to reproduce in coupled GCMs (see §2.4 of this report). This is particularly important in applications of climate model results that depend on regional details of the simulations. For example, we have been using this method to improve our understanding of the role of monsoon variability in the incidence of cholera in Bangladesh, where marked annual cycles and interannual variability in the outbreaks of that disease are highly suggestive of a climatic influence (Pascual et al., 2000). Comparing the rank-correlation maps of cholera in Bangladesh correlated with SST everywhere (Fig. 4.1.5) and the warm-cold ENSO SST pattern (Fig. 4.1.4) we find that the two are very similar. This suggests that warm winter-ENSO events act to enhance cholera outbreaks and cold winter-ENSO events suppress cholera outbreaks. Obviously, there can no direct influence on fall cholera in Bangladesh by winter Pacific SST. Thus, the enhancement/suppression of cholera outbreaks must be due to modification of the regional climate of Bangladesh by the SST anomalies. It is also possible that ENSO plays no role in influencing cholera and the correlations arise due to other, confounding variables.

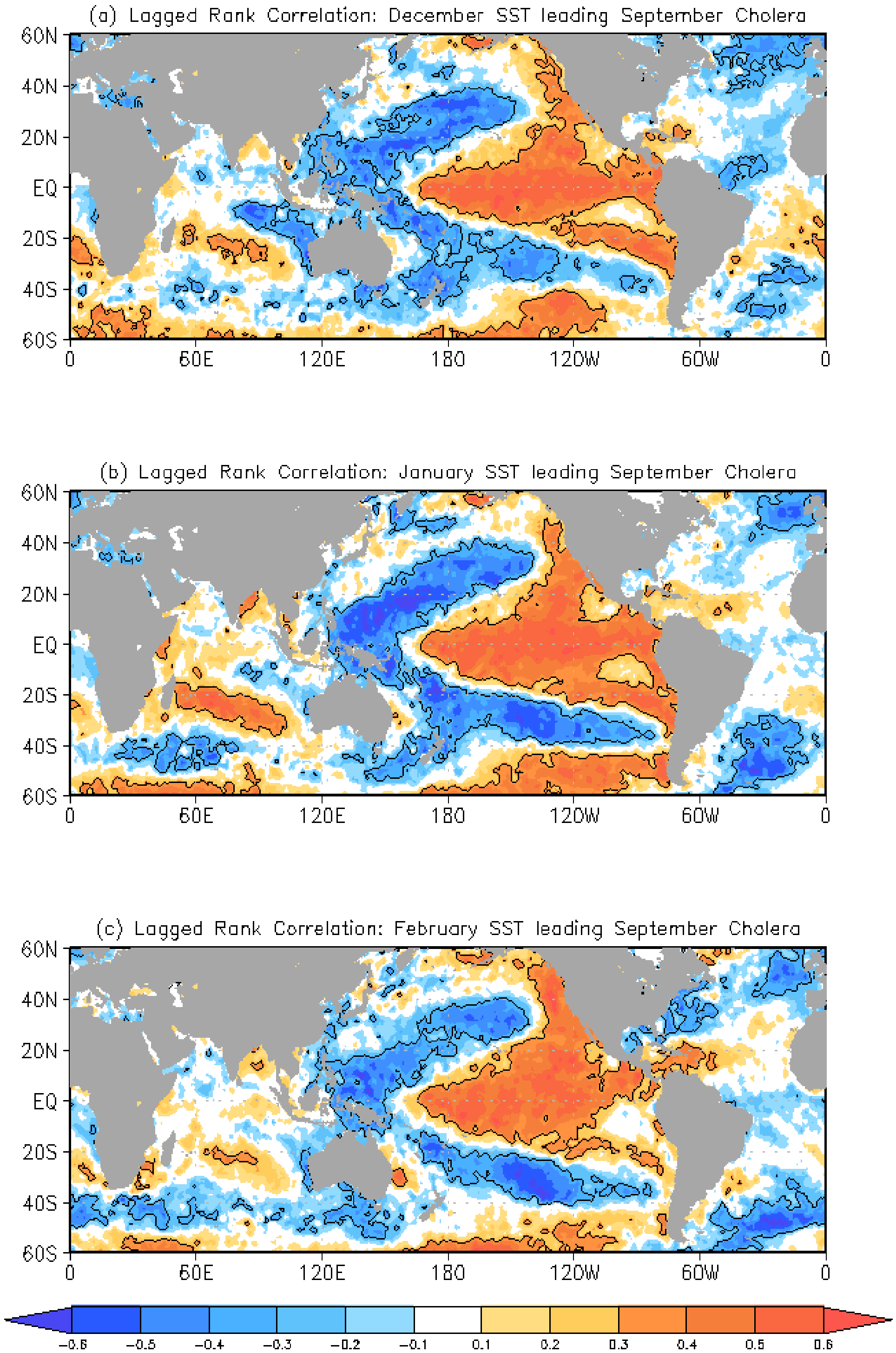

Figure 4.1.5*: Lagged rank-correlation between September El Tor cholera cases and preceding a December, b January and c February SST. Contours denote regions significant at the 90% level.*

4.1.4.2 Experiments with CFS

Modeling pacemaker experiments were conducted with the NCEP Global Forecast System (GFS), which is the atmospheric component of the CFS, coupled to a simple slab ocean mixed-layer model.

To optimize the experimental design, several experiments were performed. For the pacemaker (specified SST) region, the eastern tropical Pacific (165-290°E, 10°S-10°N), where the role of ocean dynamics is relatively important, was selected and observed SST (HadSST1.1, Rayner et al. 2003) was prescribed. The seasonally varying zonal mean mixed-layer depth was prescribed outside the pacemaker region to reflect the observed seasonality. To prevent the climate drift in this simple coupled system, weak relaxation coefficients with 15 $W/m^2/K$ were used. A 56-year simulation from 1949 to 2004 with 4 different initial conditions were completed. An additional TOGA-type experiment was run using climatological SST outside the pacemaker region instead of coupling with the slab ocean model. This run is used as a "control" for the pacemaker experiment in order to evaluate the effect of local air-sea interaction. The CFS CGCM free run of 52-year duration was also compared to consider the performance of a state-of-the-art coupled model.

The primary subjects of interest in these experiments are local air-sea feedback and the remote response to ENSO, and the ENSO-monsoon relationship as an example of air-sea coupled co-variability. The pacemaker experiments reproduce many of the atmosphere-ocean relationships including the simultaneous relation of rainfall and latent heat flux to SST over the coupled region, in particular, the monsoon convergence zone where the atmosphere forces the ocean. Comparing the pacemaker with a CGCM long run, the cause of errors in the fully coupled model can be analyzed. And the difference between pacemaker and control run shows the influence of air-sea interaction on climate variability.

Figure 4.1.6 shows the observed and simulated interannual SOI during the period of 1950–2002. The simulated SOI indices in both the pacemaker and control runs are roughly in good accordance with the observed interannual time series. However, simulated SOI in four pacemaker runs look more similar to the observed, compared to the control run. The air-sea interaction over the ocean outside the pacemaker region therefore has an important role to reproduce the realistic atmospheric response associated with ENSO.

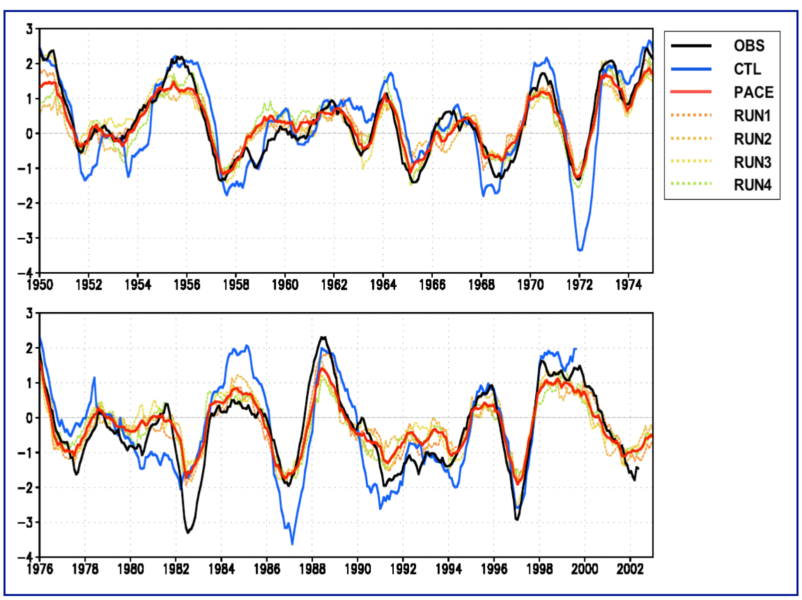

***Figure 4.1.6**: The 9-yearrunning averaged Southern Oscillation indices defined as Tahiti (145°W-155°W, 20°S-15°S) minus Darwin (125°E-135°E, 15°S-10°S) sea level pressure anomalies during 1950-2002. Black solid line denotes observed based on NCEP/NCAR reanalysis, blue denotes the control run, red denotes the ensemble mean of pacemaker runs, and dashed lined are for four individual member of pacemaker, respectively.*

To clarify the effect of local and remote forcing on the atmospheric response, the partial correlation was calculated for the SST-rainfall relationship. We used the NINO3.4 index as a representation of remote forcing. Partial correlation can discern the relationship between rainfall and local SST while removing the intercorrelated component between local and eastern Pacific SST anomalies, and vice versa for remote forcing. Figure 4.1.7 shows the simultaneous relationship of JFM mean anomalies. Compared to the CGCM, the simulated relationship in the pacemaker ensemble looks more qualitatively similar to the observed. In particular, it has a more realistic relationship over the pacemaker region, implying that the CGCM may have erroneous ENSO dynamics. This kind of error in the CGCM can degrade not only the local relationship but also the globally teleconnected response. The CGCM overestimates the positive local relationship over the northwestern Pacific and the northern Indian Ocean. The negative relationship associated with the monsoon convergence zone near Indonesia and northern Australia is reproduced in both coupled runs. The pacemaker experiments also show an improved remote response over the western Pacific, where the CGCM overestimates the extension of the positive correlation.

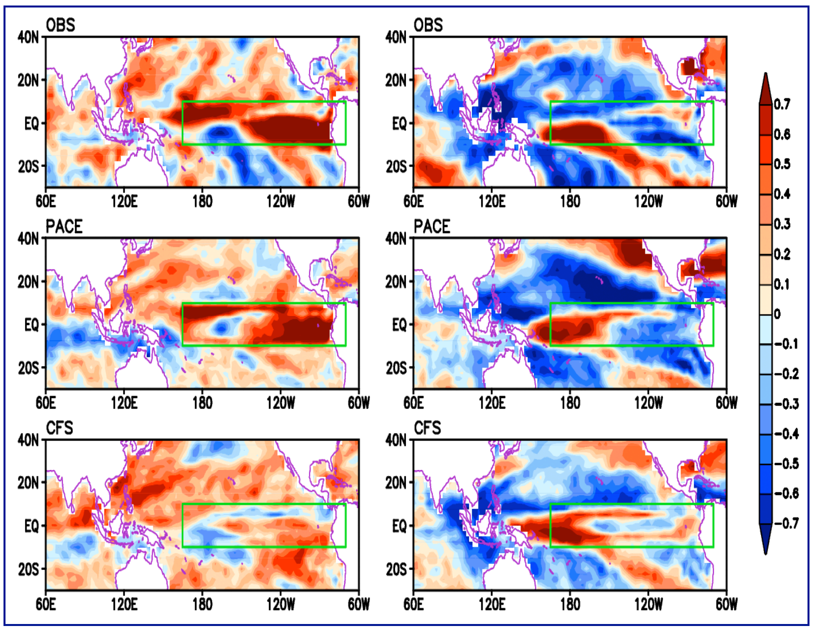

***Figure 4.1.7**: The partial correlation coefficients of precipitation anomalies related with the January-February-March local SST (left) and NINO3.4 index (right). 26-year observation data during 1979-2004 (upper) is used, 55-year data during 1950-2004 is analyzed for pacemaker (middle), and the 50-year data is used for CFS CGCM run, respectively. Green box denotes the pacemaker region.*

The evolution of the lead-lag ENSO-Indian monsoon relationship is not only a good example of air-sea coupled co-variability, but also an interesting subject for this model because the long run of the CFS CGCM cannot mimic this relationship (Fig. 4.1.8). In the control run without a coupled ocean, it is also less well simulated, as shown in an earlier study (Wu and Kirtman 2004). Surprisingly, the simulated relationship in the pacemaker ensemble is reasonably close to the observed except for its underestimate of the leading peak and overestimate of the lagging peak. These discrepancies may come from the experimental design, because only the remotely forced variability is permitted. The improvement in the pacemaker experiment compared to the CGCM simulation shows that simple systems with the only local air-sea feedback are capable of greater realism than sophisticated coupled models, since the CGCM has significant errors in the ocean dynamics and the Walker circulation related with ENSO.

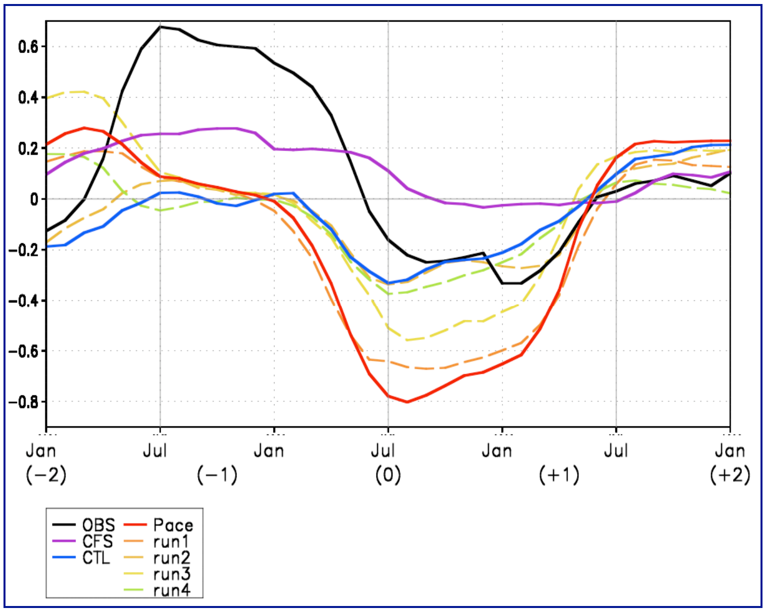

Figure 4.1.8: *The evolution of lag–lead correlation of monthly NINO3.4 SST anomalies with respect to JJAS Indian monsoon rainfall (extended IMR, an average of summer rainfall over the region of 5–25oN, 60–100oE) derived from observation (black), CFS CGCM long run (purple), TOGA control run (blue), ensemble mean of pacemaker runs (red), and individual pacemaker run (dashed lines).*

The interdecadal change of the ENSO-monsoon relationship that may be associated with global warming has been an important subject of recent climate research (e.g., Kumar et al. 1999; Chang et al 2001; Kinter et al. 2002; Annamalai and Liu 2005). Figure 4.1.9 shows the evolution of the lag–lead correlation of monthly NINO3.4 SST anomalies with respect to JJAS Indian monsoon rainfall, using a sliding 20-year window. Consistent with Fig. 4.1.8, the CGCM shows the strong positive relationship for a portion of the period when SST leads, while the control run shows the negative relationship is almost simultaneous. The pacemaker ensemble shows both a stronger relationship over the whole period and reproduces the observed weakening of the relationship after the mid-1970's. This result also supports the idea that the change of global teleconnections such as the ENSO-monsoon co-variability can be captured by a simple coupled system suggesting that the decadal change of ENSO-monsoon relationship may be a result of the change of SST variability over the eastern Pacific.

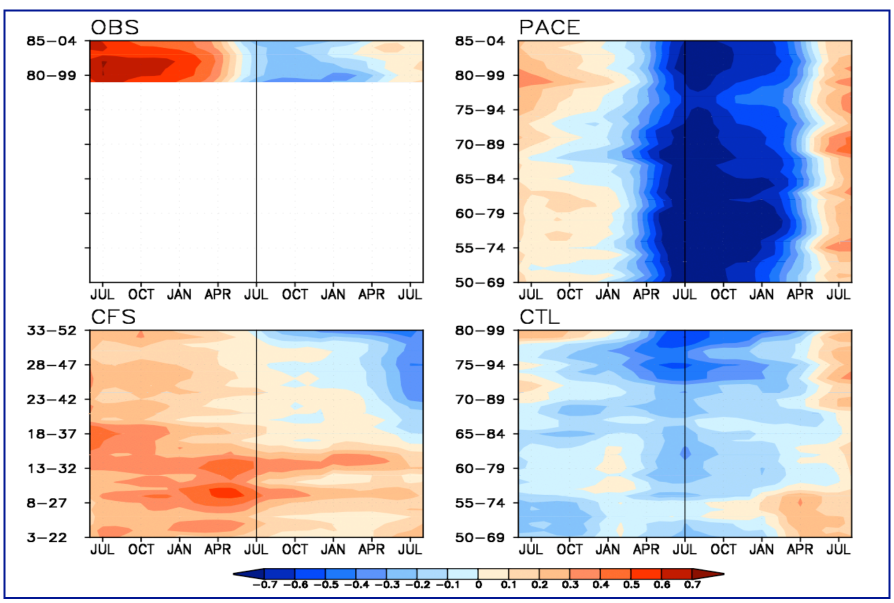

Figure 4.1.9: *Observed and simulated evolution of lag–lead correlation of monthly NINO3.4 SST anomalies with respect to JJAS Indian monsoon rainfall by moving the center of 20-year window. X-axis denotes the lead-lag month and y-axis is for the period of moving window. Black line denotes the zero lead month.*

4.2 Effect of Tropical Land Use Change

Given current demographic pressures, significant changes in tropical land use, such as large-scale deforestation of tropical rain forests, are highly probable in the 21st century. Tropical land use change will alter the physical characteristics of the surface and consequently affect the surface fluxes of heat, momentum and moisture. These will feed back on and affect the rest of the climate system. Types of possible climate changes include those to the mean state, variability, and predictability, and additionally these three aspects are all tightly tied together. We are investigating the potential climate response to tropical land use change by numerical experiments with coupled GCMs.

Previous studies have examined the potential effects of tropical land use change on mean climate in the context of an atmosphere-land coupled GCM with specified SST. We are extending these investigations to examine the effects on the mean climate and the seasonal-to-interannual variability of the coupled atmosphere-ocean-land climate system.

Our experiments were motivated by the results obtained by Hu et al. (2004), where it was found that ENSO variability in the COLA CGCM is sensitive to soil moisture conditions over the Amazon. This result suggested that more physically consistent changes in vegetation type could influence ENSO variability, and hence potentially the global climate system. We chose to make a radical change in the Amazon vegetation, as this is a first investigation of this potential impact. Investigation of more realistic changes is warranted if the radical changes have a significant impact.

Century-long simulations with the COLA CGCM have been made to examine the effect of Amazon deforestation on the coupled climate. These are described in Schneider et al. (2006). As shown in Fig. 4.2.1, the Amazon deforestation leads to changes in the precipitation over land as well as changes in the mean state over the tropical Atlantic and Pacific Oceans, and the variability over the tropical Pacific. We demonstrated that the increased variability over the tropical Pacific is caused indirectly by the changes in the mean state, and in particular the wind stress, and not directly by increased noise forcing. Diagnostic simulations with a simple atmospheric model trace the changes in the ocean mean state back to competing effects of changes in surface temperature (increase) and deep heating (decrease) over the Amazon induced by the deforestation, with the surface temperature effect enhancing the mean state changes over the surrounding oceans, and heating opposing (Fig. 4.2.2). However, the COLA CGCM is strongly deficient in rainfall over the Amazon, which raises serious concerns that the mechanism found for the changes in this model may not apply to the real climate system. In particular, the strong sensitivity of the surface temperature to deforestation is probably in large part a consequence of the dryness of the surface. For a dry surface, changes in the surface fluxes must occur through the sensible heat flux, which in turn depends on the surface temperature. If the surface were wetter, the surface could adjust by changes in the latent heat flux with much smaller surface temperature changes.

Because of these concerns, we are currently repeating the same experiment with the NCEP CFS. Over the Amazon, the CFS has a much more realistic climatological rainfall and consequently much more realistic soil moisture than the COLA CGCM.

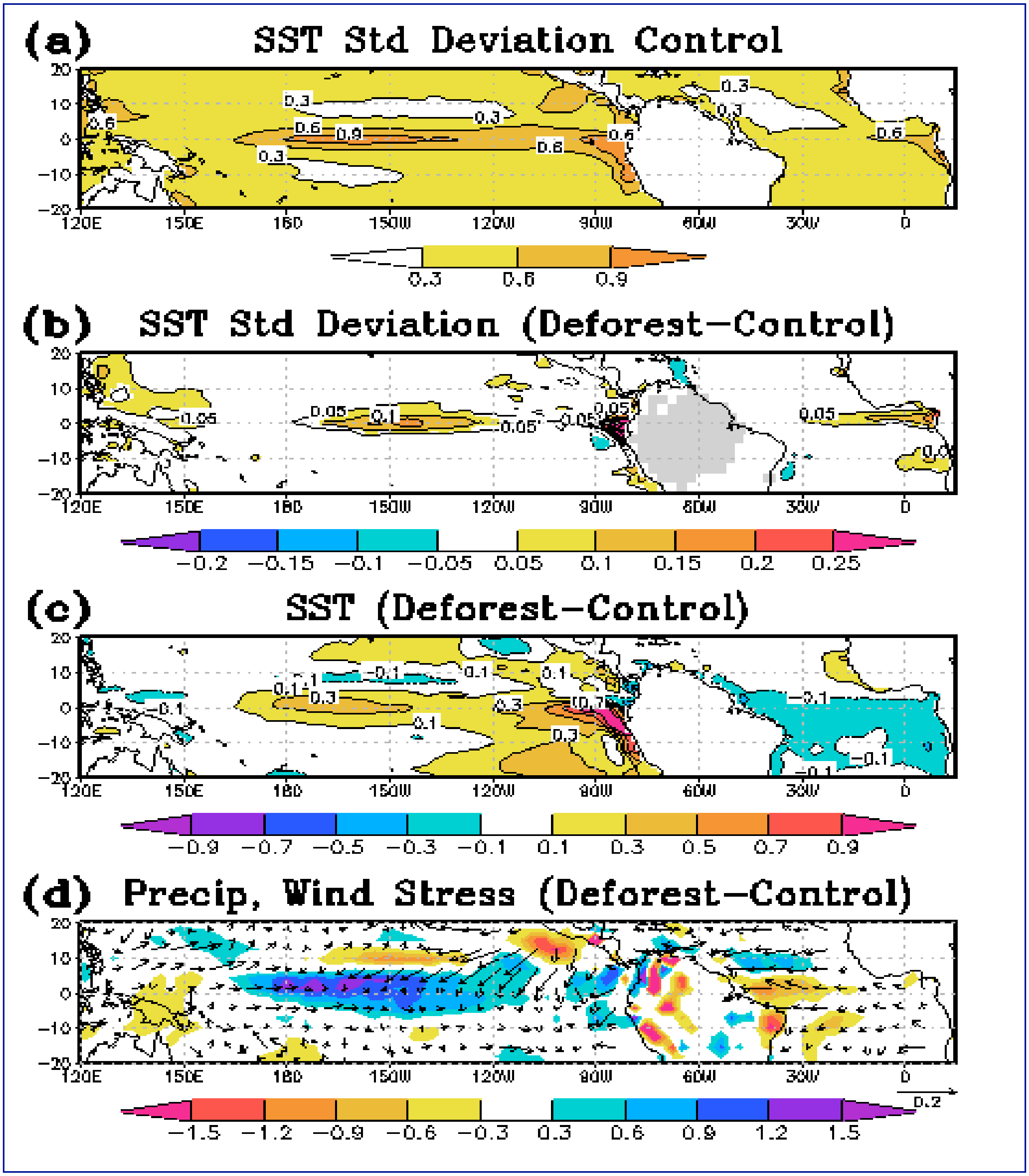

Figure 4.2.1: *Effects of Amazon deforestation on the coupled climate from 100 years of simulation. (a) Standard deviation of CONTROL SST anomalies (°C). (b) Difference of standard deviations of SST anomalies, DEFOREST minus CONTROL. Colored regions are significant at the 5% level. Deforested region is indicated in grey. (c) Annual mean SST difference (°C), DEFOREST minus CONTROL. (d) Difference in annual mean precipitation (shaded, mm day-1) and wind stress on the ocean (vectors, dynes cm-2), DEFOREST minus CONTROL.*

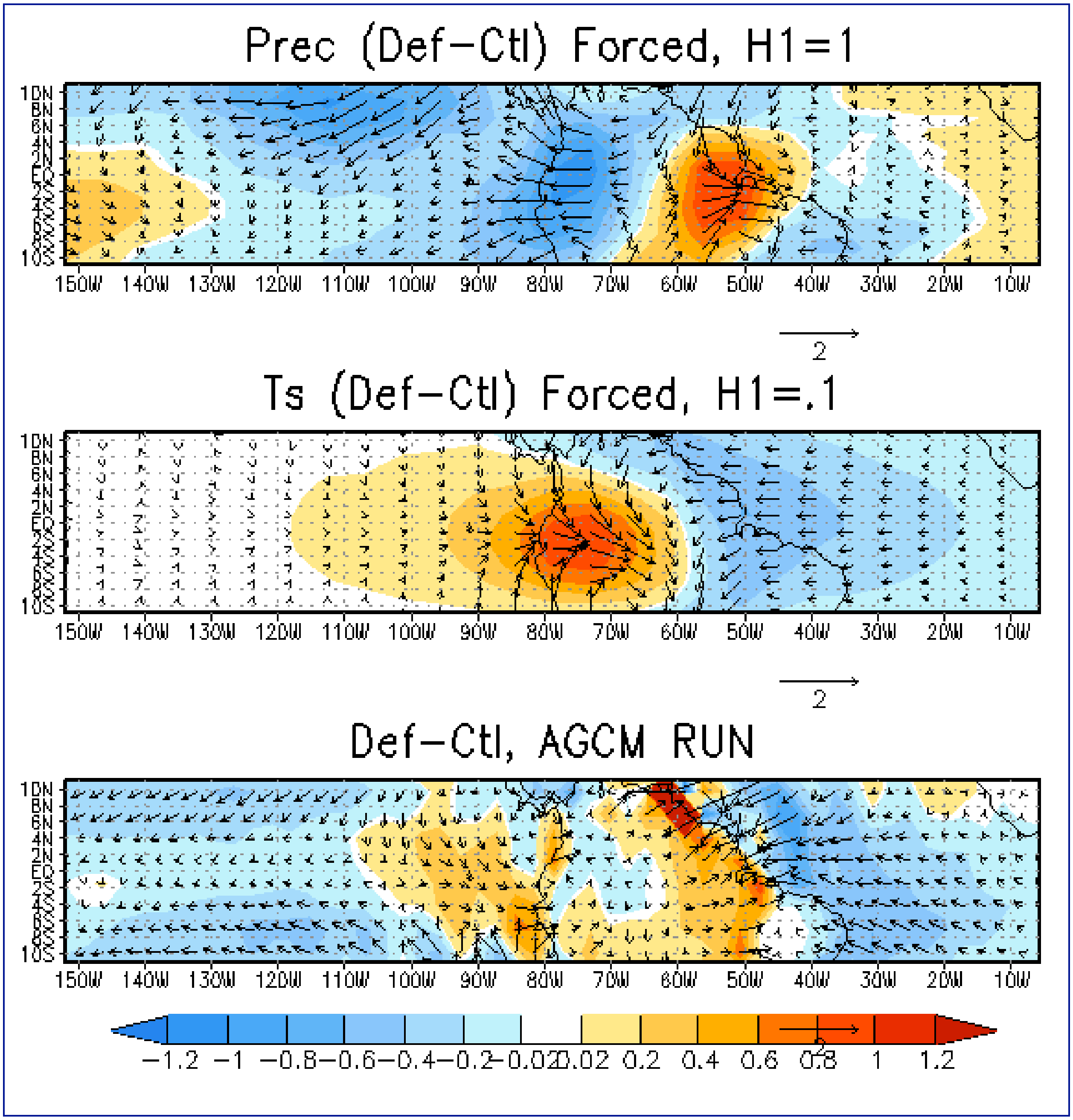

Figure 4.2.2*: Scaled surface wind response, deforest minus control, of simple Gill-type model to forcing obtained from the AGCM-only simulations with specified climatological SST. (a) Forcing by precipitation anomalies, representing atmospheric heating. (b) Forcing by land surface temperature anomalies. (c) Response from AGCM simulations. Shading represents the zonal component. See text for details.*

4.3 Effect of Global Warming on Remote Impacts of ENSO

Greenhouse gases are certain to have significant impacts on the Earth's climate, which, in the absence of other influences, will become increasingly evident. These impacts include generally increasing temperatures at the Earth's surface, rising sea level, and changes in the atmospheric and oceanic circulations. While most effort is currently focused on changes in the mean climate, it is also possible that there will be important changes is the characteristics of the seasonal-to-interannual climate variability, especially that related to ENSO, and the predictability of this variability. However, the current generation of state-of-the-art global climate models has serious problems that make projections of the details of these changes highly uncertain. These problems include:

1. The models have large biases in the simulation of the current climate, including errors in the tropics in the annual mean SST, the annual cycle of SST variability, and the spatial and temporal structures of ENSO variability. The biases of the models are model-dependent (Schneider 2002). The veracity of the simulation of the statistics of the current climate is the only verification of the realism of the models. Therefore, the justification of the application of the models to future climate is that they produce the best answers that can currently be given to the important practical questions concerning climate change. However, the realism of these answers cannot be assessed in an absolute sense.
2. Some aspects of the projections of the changes from the current climate, induced by greenhouse gas concentration increases, differ drastically among models (Cash et al. 2005, Cash et al. 2006).
3. The reasons behind the differences among the models in both their simulation of current climate and their projections are poorly understood (Schneider 2002; Cash et al. 2005; Cash et al. 2006). Given this lack of understanding, the models are treated as equally likely representations of the physical climate system, although this is undoubtedly not the case.

Given the biases of the current models in the simulations of the tropical mean state and ENSO in the current climate, projections of changes in the spatial and temporal behavior of ENSO and projections of changes in ENSO predictability are just not believable. We are developing and testing a methodology to constrain projections of some aspects of ENSO by examining the effect that model projections of the changing mean climate would have on the response to the ENSO SST variability of the current climate. This methodology is to perform time slice experiments with changes in climatological SST produced by projections of future climate superimposed on the observed SST evolution of the current climate. This approach guarantees that the ENSO SST anomalies will have physically realizable structures and time variability. Comparison of the response to ENSO in current climate simulations allows the effect of the mean state changes to be examined and quantified.

Many of the issues associated with this technique have been examined in the experiments described by Cash et al. (2005), where the causes of different regional sensitivities of midlatitude mean atmospheric circulation to doubled CO_2 between CCM3 and ECHAM4.6 were diagnosed. There, the different changes in the midlatitude stationary waves of the two models were traced in some regions to different changes in tropical SST, transmitted to the atmospheric circulation by different deep convective heating, while the different responses in other regions was found to be due to different atmospheric responses to the same heating. It was also found there that changes in midlatitude SST were of secondary importance with regard to changes in the midlatitude atmospheric circulation.

We are using the new version of the NCAR AGCM, CAM3, in the examination of the atmospheric response to realistic ENSO SST anomalies. The monthly-varying change in the mean SST is taken as the ensemble mean of the runs with the new NCAR coupled model, CCSM3 that were collected for the IPCC. Future climate is represented by the average over years 2065-2075 from 9 runs with greenhouse gas forcing from the A1B scenario, while current climate is the average over 1965-1975 from 9 runs with historical forcing. The climatological changes are then added to the observed time-evolving SST over 1951-2001, and the response of CAM3 to this new time-evolving SST forcing is found from an ensemble of integrations with different atmospheric initial conditions. Preliminary results are described below.

Figure 4.3.1a shows the seasonal means of the difference in SST forcing found from the IPCC runs and specified in our experiments. SST warming is about 2°C in the tropics, decreasing in the subtropics, and then increasing in midlatitudes. The model responds to this new forcing by producing changes in the mean state, including changes in the mean precipitation and atmospheric mean circulation. The DJF changes in the mean precipitation and 500 hPa geopotential height are shown in Fig. 4.3.1b and 4.3.1c, respectively. There are precipitation increases of a few mm day^{-1} in the equatorial Pacific, with the largest increases east of the dateline. The 500 hPa geopotential height increases everywhere, with some wavelike behavior in the Northern Hemisphere extratropics, and more or less zonally symmetric in the Southern Hemisphere.

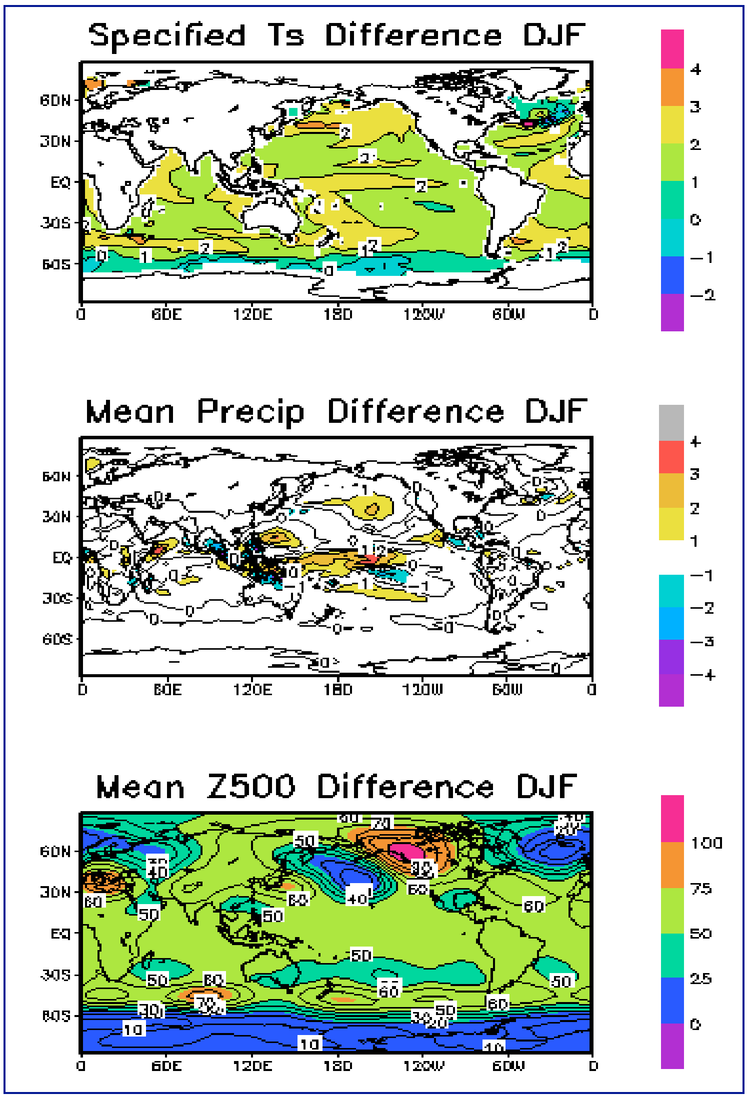

Figure 4.3.1: *Difference between DJF mean of 2065-2075 and current climate time slice simulations. a) SST (degrees); b) precipitation (mm day-1); c) 500 mb geopotential height (m).*

The atmospheric response to the ENSO SST anomalies also changes, despite the fact that the anomalies are the same in the specified current and future SST anomalies. The changes in the precipitation response to the SST anomaly is represented in Fig. 4.3.2a by the change in the regression of the monthly precipitation anomalies onto the simultaneous NINO3.4 SST anomaly. The major signal is an increase in the sensitivity of the precipitation anomalies to the SST anomaly in the central equatorial Pacific. The changes in the midlatitude atmosphere circulation anomalies are represented in Fig. 4.3.2b by the change in the regression of the monthly 500 hPa geopotential height anomalies onto the simultaneous NINO3.4 SST anomaly. There are wavetrains symmetric about the equator apparently emanating from the tropical Pacific with a structure similar to that of the response to NINO3.4 in the control simulation (not shown). The future climate case then produces an intensification of the midlatitude response to NINO3.4 approximately in proportion to the increase in the precipitation response. That is, there is an increased midlatitude response produced by the stronger tropical heating response. There is also another set of wavetrains apparently emanating from the Central/South American region and arcing across the North and South Atlantic. There is no obvious heat source associated with these Atlantic wave trains, but they could possibly be associated with changes in the mean state. It remains to be determined if this feature is statistically significant and if so, what its origin is.

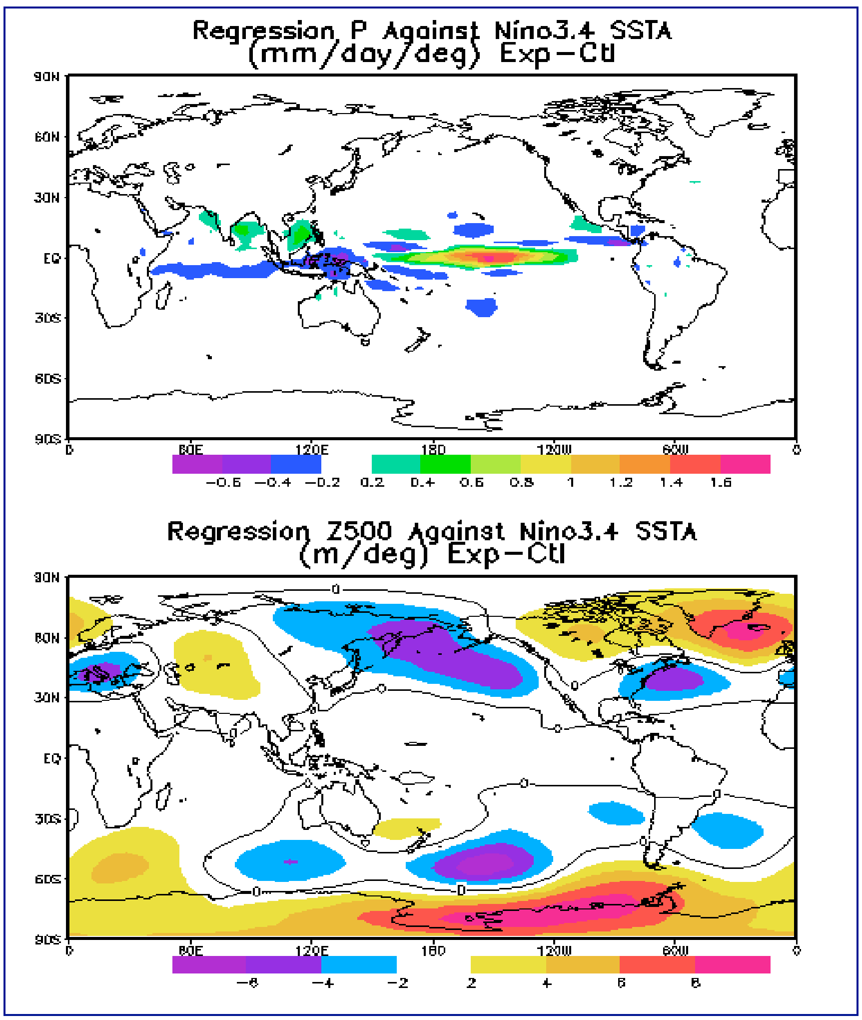

Figure 4.3.2: *Difference of regressions against Nino3.4 SST anomalies from 2065-2075 minus current climate time slice simulations. a) Precipitation (mm day-1 °C-1); b) 500mb geopotential height (m °C-1).*

We are planning to examine the model dependence of these results by using changes in the climatological SST from the different IPCC coupled models, as well as a mean over all models, and by carrying out the time slice simulations with different AGCMs.

4.4 Model Fidelity and Sensitivity to Greenhouse Gas Concentrations

The models used in the IPCC Fourth Assessment Report (AR4) were found to have varying degrees of agreement with the observed climate record (Shukla et al., 2005). Relative entropy, which is a measure of the difference between two probability distributions, has been calculated for the simulations of the climate of the 20th century from 13 IPCC AR4 models and the observed surface air temperature during the past 100 years. This quantity is used as a measure of model fidelity: a small value of relative entropy indicates that a given model's distribution is close to the observed. It is found that there is an inverse relationship between relative entropy and the sensitivity of the model to doubling of the concentration of CO_2 (Fig. 4.4.1). The models that have lower values of relative entropy, hence higher fidelity in simulating the present climate, produce higher values of global warming for a doubling of CO_2. If models that better simulate the present climate can be considered more credible in projecting the future climate change, then this relationship suggests that the actual changes in global warming will be closer to the highest projected estimates among the current generation of models used in IPCC AR4.

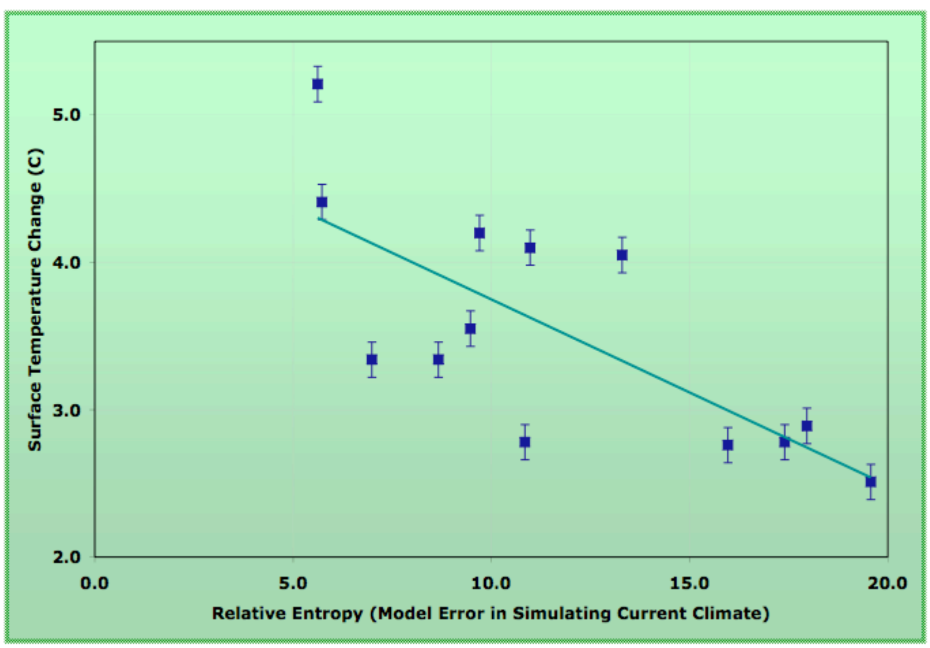

Figure 4.4.1: *Model sensitivity (surface air temperature change over land) versus model relative entropy for 13 IPCC AR4 models. Estimates of the uncertainty in the surface temperature change are shown as vertical error bars. The line is a least-squares fit to the values.*

5. ESTIMATES OF PREDICTABILITY AND MODEL VALIDATION

5.1 Quantifying Predictability

An event is unpredictable if the corresponding forecast distribution is identical to the climatological distribution. It follows from this definition that a necessary condition for an event to be predictable is for its forecast distribution to differ from the climatological distribution. Thus, measures of predictability depend on measures of the difference between two distributions. Leung and North (1990), Schneider and Griffies (1999) and Kleeman (2001) proposed that measures from information theory, in particular mutual information, predictive information, and relative entropy, respectively, provide attractive measures of predictability. DelSole (2004) proposed a probabilistic framework that clarified that all of these measures reduce to the same quantity when averaged over all forecasts. Furthermore, under suitable Gaussian assumptions, these measures can be decomposed into an uncorrelated set of structures that can be ordered by their contribution to the predictability measure; the individual terms are called "predictable components" and the associated technique predictable component analysis (PrCA). This framework makes manifest the equivalence between problems in predictability and certain problems in multivariate statistics. This unifying framework contributes to establishing a rigorous foundation for the application of advanced multivariate statistical techniques, such as pattern recognition and data mining techniques, to weather and climate. This framework also can be formulated in such a way as to avoid the fictional "perfect model scenario," which provides the basis for most other predictability studies. This more general formulation introduces the concept of potential predictable components, which define predictors that capture the full predictability of the system without loss of generality (DelSole 2005).

One of the outstanding issues in predictability theory is identifying components that are predictable and those that are unpredictable. Several papers have suggested that singular vectors can be used to identify these components (Lorenz 1965; Penland and Sardeshmukh 1995; Kleeman et al 2003). A key question with singular vectors is what norm should be used to measure the initial and final states. This question has received surprisingly little attention in the literature. Recently, DelSole and Tippett (2006) showed that information theory imposes well-defined norms for singular vectors. In the case of the final state, information theory implies that the appropriate norm corresponds to dividing the evolved amplification by the climatological variance, or equivalently, computing the signal-to-noise ratio (where "signal" refers to ensemble mean forecast and "noise" refers to deviations about ensemble mean). This norm contrasts with norms that measure only the signal part of the signal-to-noise ratio. By accounting for signal and noise simultaneously, the resulting norm maximizes signal-to-noise directly, and therefore yields structures with more predictability. For the initial states, information theory implies that the appropriate norm corresponds to constraining the initial amplitudes to lie on a surface of equal probability density defined by the climatological distribution. In other words, the initial states are "equally likely" under the climatological distribution. This norm resolves the criticism that singular vectors may be "unphysical" because they may require structures that occur only rarely in the system. By imposing this norm, the leading singular vectors are guaranteed to be just as likely as any of the other singular vectors. Surprisingly, the norms implied by information theory do not appear to have been used in any study of predictability. Nevertheless, the above considerations suggest that the norms implied by information theory are sensible and can improve predictability estimates.

5.2 Contributions to Statistical Science

An outstanding question in prediction theory is whether forecasts from different models can be combined to produce a single forecast with improved skill. For seasonal forecasts, the available record is too short to apply ordinary least squares. The essential problem is that if the number of models is not a small fraction of the total sample size, then ordinary least squares suffers from the fact that the method fits variability due to sampling errors. Several methodologies have been proposed to account for small sample sizes, from filtering based on singular value decomposition (Krishnamurti et al. 1999, 2000, 2001; Yun et al. 2003) to Ridge Regression (van den Dool and Rukhovets 1994) to "forecast assimilation" (Stephenson et al. 2005) to Bayesian methods (Raftery et al. 2005; Rajagopalan et al. 2002; Robertson et al. 2004). DelSole (2006) recently showed that these methods, as well as a host of others, can be interpreted as special cases of a more general Bayesian framework. Bayesian theory allows one to incorporate "prior beliefs" in the estimation process. Prior beliefs are essential in regression theory when the number of predictors is not a small fraction of the sample size. Bayesian theory therefore clarifies the implicit prior beliefs that are being imposed on the estimates, whether users are aware of them or not. DelSole (2006) proposed several new multimodel methods based on a new set of prior beliefs appropriate to multimodel methods. The new multimodels were tested on the DEMETER hindcasts of seasonal mean 2m temperature over land. The spatially averaged correlation skill of the multimodel methods over North America are shown in Fig. 5.2.1 (the different forecast schemes are denoted R:0, R:MM, R:MM+R, R:S2N, but the details are not essential; LS denotes ordinary least squares, MMM denotes the simple mean of the forecasts, and S2N is a signal-to-noise maximizing method). Surprisingly, none of the regression models examined in DelSole (2006), including ridge regression, could improve on the skill of a simple multimodel mean, despite the fact that one of the regression models (R:MM) recovers the multimodel mean in a suitable limit. This last result clearly demonstrates that the methods used to select empirical parameters in the multimodel combination were flawed. Closer scrutiny revealed that the source of the problem was that the selection methods were themselves sensitive to sampling errors. Since the vast majority of multimodel methods contain similar empirical parameters, we believe that the phenomenon found here constitutes a significant barrier to all multimodel regression methods. We are currently investigating a new method for overcoming this problem. Despite the above conclusions, the results from the multimodel mean shown in Fig. 5.2.1 demonstrate that seasonal mean 2m temperature is predictable for at least three months.

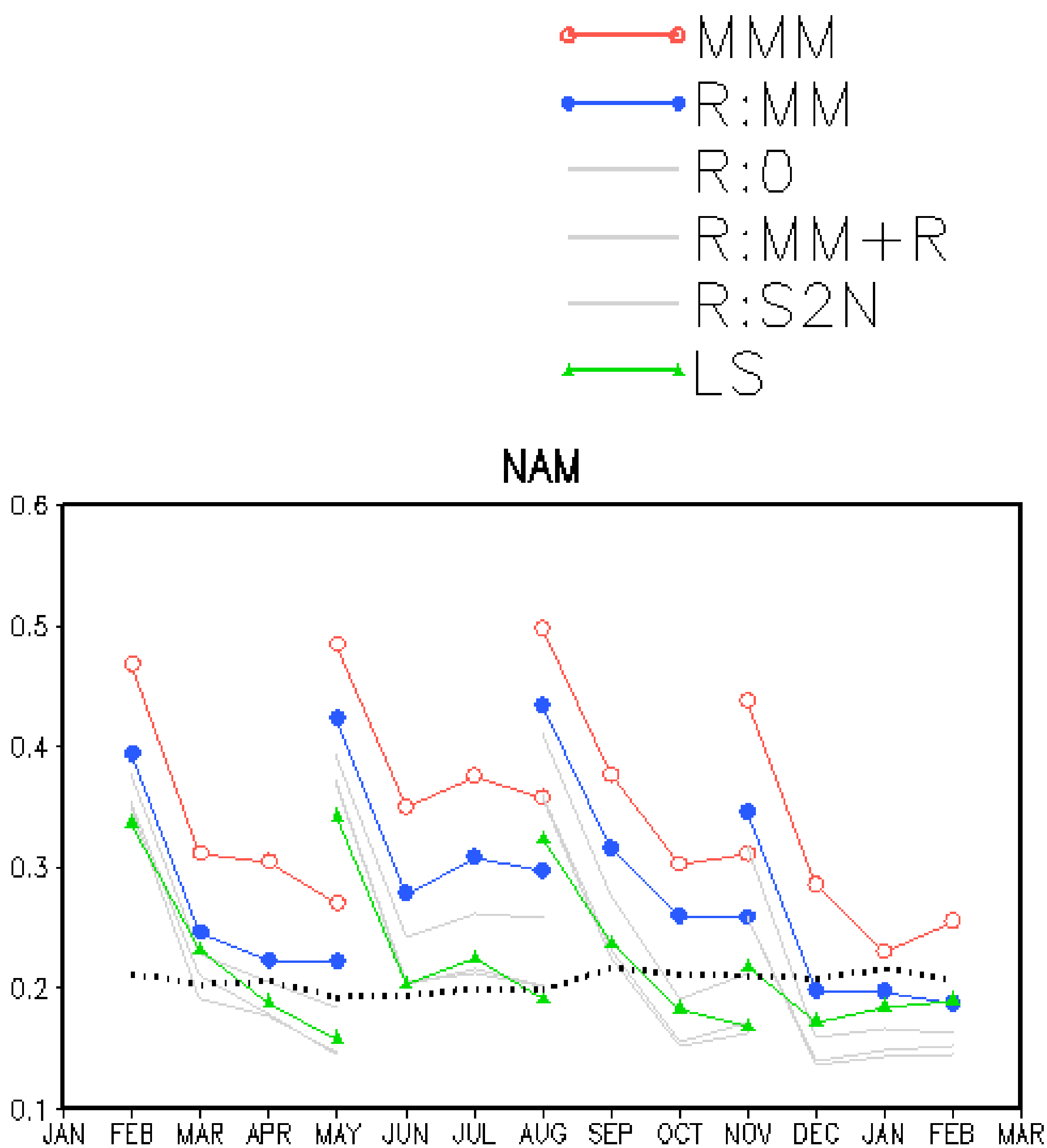

Figure 5.2.1: *Area averaged correlation skill of 2m temperature over land for the multimodel combinations considered in DelSole (2006). The forecasts were selected from the DEMETER project for the period 1980-2001 over North America. The multimodel mean (MMM) and ordinary least squares (LS) also are shown. The month label refers to the first month of the 3-month average (e.g., "JUN" refers to the JJA). Forecasts from the same initial condition are joined by a line. The horizontal dotted line gives the 1% significance level of correlation skill.*

A major barrier to climate studies is the lack of an effective method for separating slowly varying components (i.e., droughts and heat waves) from rapidly varying components (i.e, daily weather). A popular approach to isolating slowly varying components is to apply principal component analysis to a filtered time series in which rapidly varying fluctuations have been removed. This approach is problematic because the resulting principal component may dominate variations on slow time scales simply because it dominates variations at all time scales. An alternative approach is to compute long-term means or trends. These latter approaches do not efficiently capture space-time variations, or presume a slowly varying signal that is a linear function of time. DelSole (2001) proposed a new technique, called optimal persistence analysis, which essentially decomposes data by time scale. More precisely, this technique decomposes data in terms of spatial patterns and corresponding time series, ordered such that the first component has the slowest time scale, the second has the slowest time scale subject to being uncorrelated with the first, and so on, where "time scale" is measured by the decorrelation time of the autocorrelation function of the time series. This method represents a substantial advance over previous methods, since it isolates slowly varying signals with a small number of spatial patterns and their corresponding time series, and allows time variations to be a nonlinear function of time. DelSole (2006) extended this technique in the following ways. First, optimal persistence analysis was shown to have an intimate connection with power spectrum analysis. Indeed, the decorrelation time is precisely equivalent to the ratio of the "smoothed" power at zero frequency to the total power, which ensures that the time series has large power at low frequencies *relative to other frequencies*. Second, an objective criterion for deciding the number of principal components for representing the optimal persistence pattern was proposed. Third, a statistical significance test based on Monte Carlo methods was proposed for ascertaining whether the obtained optimal perstistence patterns are distinguishable from those that would be expected from white noise. Finally, a method for accounting for seasonal variations in the persistence patterns was introduced based on the use of Cyclostationary Principal Components. All of these advancements were brought to bear on the analysis of observational and simulated data sets related to the IPCC (DelSole 2006). One major result, shown in Fig. 5.2.2, is that only two distinct patterns in the observed temperature record are distinguishable from white noise, and that climate models tend to underestimate the decorrelation time of these patterns.

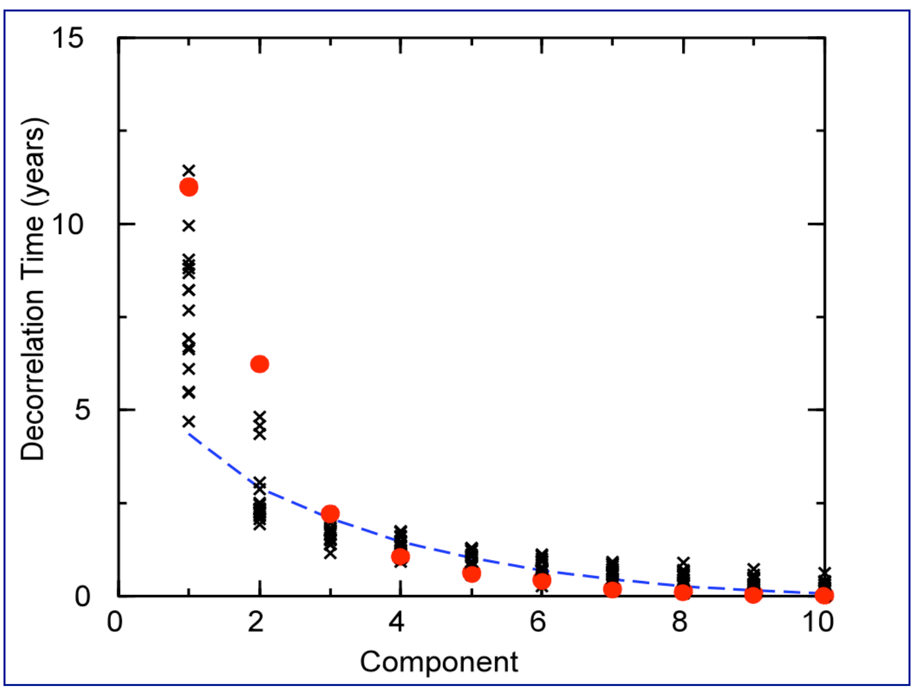

Figure 5.2.2: *Decorrelation time (in years) of all optimal persistence patterns derived from the IPCC simulations (x) and observations (filled red circles). In all cases, the OPPs were computed with 10 cyclostationary principal components of each respective data set. The dashed line shows the 99% percentile for a stationary white noise process.*

An outstanding problem in seasonal prediction is that dynamical models produce forecasts with significant biases that require some form of correction to render the associated predictions useful. DelSole and Shukla (2006) explored a variety of statistical correction methods using forecasts of wintertime North American surface temperature produced as part of the Dynamical Seasonal Prediction (DSP) project. The statistical correction methods included not only ordinary least squares, similar to Model Output Statistics (MOS), but also methods based on principal component analysis, canonical correlation analysis, and discriminant analysis. DelSole and Shukla (2006) found that no single strategy improved model hindcast skill in all cases. Contrary to expectations, the correlation skill of all GCM forecasts were found to be comparable to, if not better than, the skill of the best empirical models (for the 1982-1998 period examined). These results suggest that the seasonal predictability community has now entered into a phase in which GCMs perform at least as well on seasonal time scales as statistical models.

Canonical correlation analysis and linear inverse models provide the basis for seasonal forecasts by different operational centers. There have been various assessments in the literature as to which method is “the best.” DelSole and Chang (2003) demonstrated that forecasts based on the two methods are in fact *identical* when all canonical patterns are superposed. This result comprehensively resolves a long-standing debate about the relative skill of the two forecast methods. This paper also derived additional connections between predictable component analysis, canonical correlation analysis, and linear regression models, which appear to have been unrecognized in the climate community.

6. CLIMATE DYNAMICS

6.1 Contributions to Stochastic Models of Turbulence

Atmospheric eddies play a critical role in climate by transporting significant quantities of heat, momentum, and moisture. At present, these eddies can be predicted only with general circulation models, which involve thousands of variables and are far too computationally demanding to simulate more than a few thousand years of climate. If the statistics of eddies could be predicted without actually simulating them, then one might be able to construct an efficient climate model for millennium time scales. Stochastic turbulence models have emerged as a promising approach to predicting the eddy statistics of large-scale flows. In these models, the non-normal dynamics of eddies are captured by a suitable linear operator and the self-interaction of the perturbations are parameterized by a random forcing and systematic dissipation. The literature on these models was comprehensively reviewed by DelSole (2004) in an invited review paper. Recently, DelSole (2006) proposed a closure theory for stochastic models that not only gives reasonable predictions for the dominant eddy statistics, but also predicts the *-3* power law for the asymptotic energy spectrum.

One theory for why stochastic turbulence models appear to work in atmospheric models is that the strong background shear in atmospheric flows renders the system highly non-normal. As a consequence of this non-normality, certain "preferred" perturbations grow to large amplitude even when all normal modes of the system decay. These preferred perturbations, called optimal perturbations or singular vectors, can be identified with the dominant large-scale eddies in a turbulent system. Surprisingly, the question of whether these optimal perturbations actually exist in real turbulent simulations with the level of amplitude and frequency required to explain the energy containing eddies has not been addressed completely satisfactorily. DelSole (2004) proved rigorously that a special class of optimal perturbations, called instantaneous optimals, satisfies energy conservation on average in a statistically stationary flow. This result implies that, in the limit of short time, the net energy in the growing singular vectors must exceed, on average, the net energy in the decaying singular vectors. More recently, DelSole (2005) addressed these questions in a rigorous, self-consistent manner in a series of turbulence simulations based on the two-layer quasigeostrophic model. This study demonstrated that the amplitude variance of the singular vectors were within an order of magnitude of that needed to explain the energy containing eddies, and that the leading few singular vectors were closely related to the leading empirical orthogonal functions (EOFs).

6.2 Empirical Mode Decomposition

Over the past five years, COLA scientists, particularly Dr. Z. Wu, have been conducting research on the development of new data analysis techniques and their applications to climate science and beyond. We have made substantial progress in improving the Empirical Mode Decomposition (EMD) method, and in exploring its novel applications to climate research.

The EMD is a time-series analysis method for the general purpose of data analysis, recently developed by Norden Huang of NASA. It is a decomposition method based on the local properties of a given data set and is highly adaptive; hence it can deal with the nonlinearity and non-stationarity of the data well. The EMD has facilitated numerous important scientific findings that could hardly be achieved using any other methods, and is gaining popularity in many scientific fields.

The EMD method is sensitive to intermittent signals or noise in the data, leading to two major drawbacks: (1) a component could contain oscillations of dramatically different timescales, resulting in scale mixing; and (2) small amplitude noise contained in the data may dramatically change the decomposition, meaning that a given decomposition might not be unique in a physical sense. To overcome these drawbacks, Wu and Huang developed the Ensemble EMD (EEMD) method, which applies the decomposition to an ensemble of time series in which different samples of white noise have been added to the original time series, with the mean decomposition being treated as the final true result. In this method, finite amplitude white noise is necessary to force the ensemble to exhaust all possible solutions in the sifting process, thus making the different scale signals collate in the proper intrinsic mode functions (IMF) dictated by the dyadic filter banks. Because the EMD method operates in time space, the added white noise, which provides a uniform reference frame in the time-frequency space for collating the portion of the signal of comparable scale in one IMF, is averaged out over a sufficient number of trials. With this ensemble mean, one can separate the scales present in the data naturally, leading to the decomposition being physically unique and interpretable (not sensitive to noise). An example that illustrates the EEMD physical decomposition is provided in Fig. 6.2.1, in which the Southern Oscillation Index and the Cold Tongue Index (Deser and Wallace, 1990) are decomposed. Since these two indices reflect the two components of a coupled system, the synchronization of the decompositions is captured.

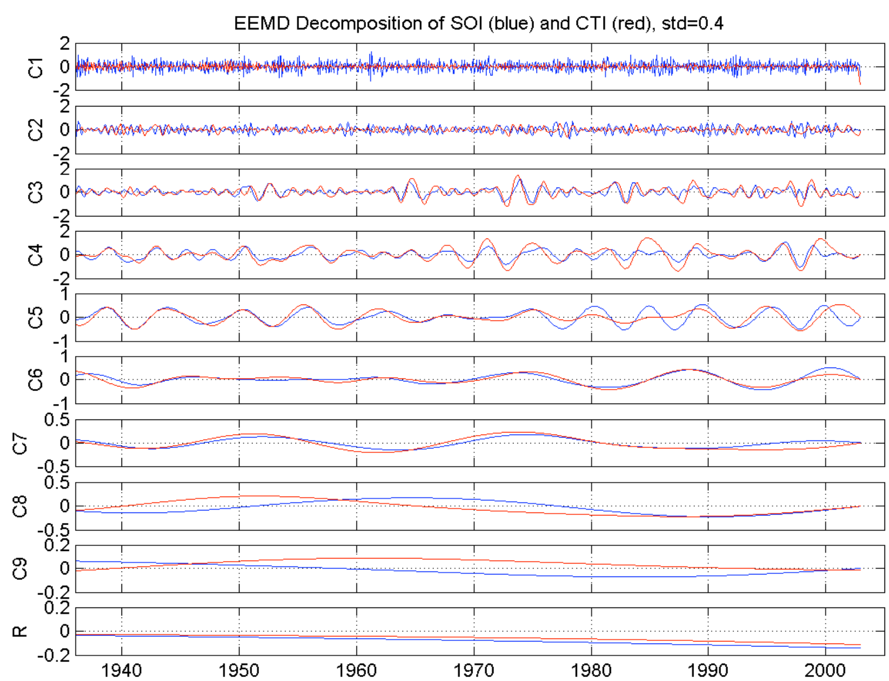

Figure 6.2.1*: The IMF-like components of the decompositions of the SOI (blue lines) and the CTI (red lines) using the EEMD. For the convenience of identifying their synchronization, the CTI and its components are flipped.*

Another major limitation of the EMD is the absence of any way to determine whether a data set or its components contain useful information, since every real-world data set contains noise. The task is essentially a binary hypothesis-testing problem in which a null hypothesis of pure noise is often used. Based on numerical experiments on various types of white noise using the EMD, Wu and Huang discovered that the EMD is effectively a dyadic filter; that the IMFs are all normally distributed, and that the Fourier spectra of the IMF components are all identical and cover the same area on a semi-logarithmic period scale. They deduced that the product of the energy density of IMF and its corresponding mean period is a constant, and that the energy density function is χ-squared distributed. They further derived the energy density spread function of the IMF components. Through these results, they established a method to assign statistical significance of information content for IMF components in any noisy data set. An example of the testing of the statistical significance of components of the Southern Oscillation Index is displayed in Fig. 6.2.2.

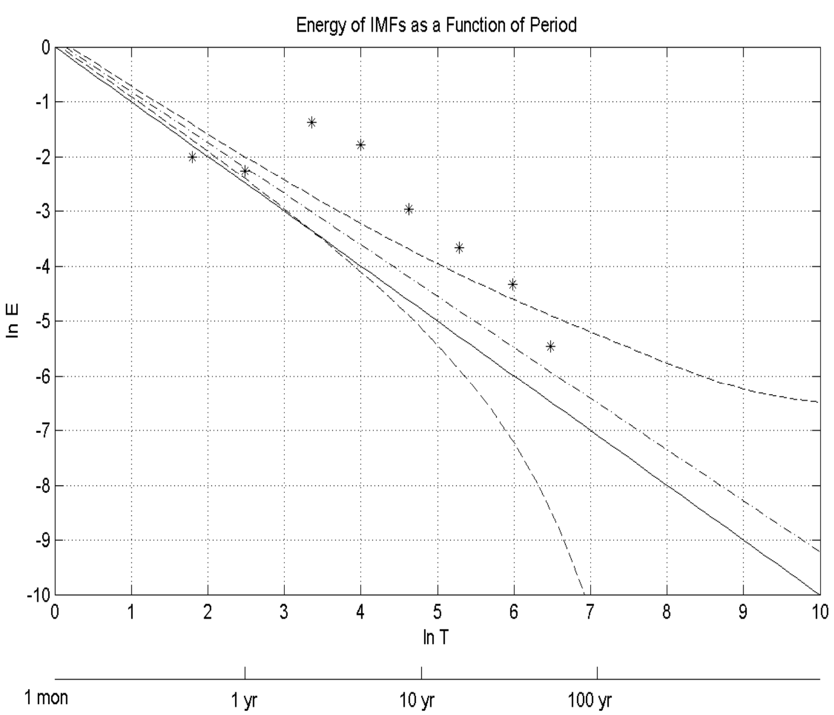

Figure 6.2.2: *Significance test of IMFs of SOI. The solid line from upper left corner to lower right corner is the theoretical line. The dash-dotted black line is the empirical fitting of the averaged mean energy density and the averaged mean period for Gaussian white noise. The dashed lines are the 5th and 95th percentiles calculated from the theory. The asterisks correspond to the pairs of the averaged mean energy density and the averaged mean period of components 2-9 of SOI (from left to right).*

The new developments have been applied successfully to facilitate new findings in climate sciences, and to reexamine our understanding of many climate phenomena.

6.3 Development of Coupled Climate Models

Misra and Marx (2006a, b) have made a persuasive case of developing coupled models in a coupled framework where atmosphere, land and ocean interact consistently. In a set of sensitivity experiments each having small changes in the parameterization of the shallow inversion clouds, Misra and Marx (2006a) showed that the response of the mean tropical Pacific climate is very different when the same COLA AGCM is forced with observed SST or when it is coupled to an OGCM (MOM3). Likewise Misra and Marx (2006b) showed that the interannual variability of tropical Pacific in the COLA coupled model is very sensitive to the choices of model parameters in the parameterization of the shallow inversion clouds.

6.4 GrADS and the GrADS Data Server

An essential component of research in basic climate dynamics is the organization and analysis of very large volumes of data from disparate sources. After more than a decade of development and support, COLA's Grid Analysis and Display System (GrADS) is universally recognized as the tool of choice among weather forecasters, climate modelers, and meteorology educators to evaluate their data and quantitatively present their results graphically. GrADS provides a de facto standard with which scientists can organize and exchange their data, metadata and figures.

The GrADS Data Server (GDS – w w w.iges.org/grad/gds/) technology, originally developed in collaboration with George Mason University under a grant from NASA, has dramatically altered the way we organize and interact with gridded and station data, not only at COLA but across the globe at hundreds of weather and climate research and educational institutions. The GDS enables users to access, subset, analyze and display data that reside on the server at COLA (or any other data distribution site that has mounted a GDS system) from a remote client, *without transporting the data sets used or having detailed knowledge of the data sets' structure or format*. The result is that data served online have a much higher value, because they can be accessed and used much more readily and with a much higher level of interoperability with other data sets. The GDS has provided an incentive for data providers to organize their data sets in such a way as to optimize access for subsetting and remote analysis from the Internet, and it has provided an incentive for users to consider much more ambitious analysis projects because they no longer have to make their own copies of prohibitively large data sets downloaded from remote sites.

To implement this capability, the technologies of GrADS and OPeNDAP (the Open-source Project for a Network Data Access Protocol – www.opendap.org; previously known as DODS) were merged on both the client and server sides. GrADS, when linked with the OPeNDAP-enabled netCDF client software library, can access data sets and subsets of data sets over the network from any of hundreds of OPeNDAP servers. The GDS server allows OPeNDAP-enabled client software to retrieve arbitrary subsets of all the data formats that GrADS supports, including GRIB. In addition, the GDS extends the capabilities of OPeNDAP by providing analysis capability on the server side. For example, one can compute an average over a very large amount of data on the server, with only the (fairly small) result being transmitted back to the client.

The GDS paradigm for remote data access and analysis has been adopted by several groups for the purposes of serving large communities, including the NOAA NOMADS project at NCEP, NCDC, GFDL and FSL (e.g. nomad2.ncep.noaa.gov/), the NASA Land Information System project (lis.gsfc.nasa.gov/), the U.S. GODAE project (www.usgodae.org/dods/GDS), the Asia-Pacific Data-Research Center (apdrc.soest.hawaii.edu), GEWEX CEOP data management (www.joss.ucar.edu/ghp/ceopdm), and the European MERSEA project (www.mersea.eu.org).

The combination of GrADS graphical software linked with the GrADS Data Server (GDS) data management capabilities and a metadata search tool called Greta permit much more rapid exchange of ideas and results both inside and outside COLA, accelerating and improving the productivity of scientists worldwide. This permits each institution to use it's locally developed analysis toolkit to examine jointly conducted experiments as well as other recent experiments in a consistent manner. Results can thus be exchanged and even reanalyzed as part of a phone conversation. Multiple results can be quickly synthesized to create a multi-institutional journal paper. GrADS and GDS are now parts of the common cyberinfrastructure that is ubiquitous in our field, but, like all good infrastructure, they are often overlooked due to their simplicity and intuitive design.

As one application of the GDS, COLA and the U.S. National Weather Service have extended low-cost weather forecast capability to the five pilot countries in the developing world by implementing the Desktop Weather-Forecast System at their national hydrometeorological services.

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7. COLA ORGANIZATION

7.1 Research, Information Systems And Administrative Personnel

The following summary biographies describe members of the COLA staff at the end of 2006.

Principal Investigators

T. DelSole, Ph.D., Harvard University, 1993. Research Scientist, COLA; Associate Professor, Climate Dynamics, George Mason University. Dr. DelSole studies climate variability and predictability using stochastic turbulence models and statistical prediction techniques. After completing his doctorate, Dr. DelSole was a Global Change Distinguished Postdoctoral Fellow for two years and a National Research Council Associate for two years at NASA Goddard.

P. A. Dirmeyer, Ph.D., University of Maryland, 1992. Associate Research Scientist, COLA. Dr. Dirmeyer conducts research on the role of the land surface in the climate system. This includes the development and application of land-surface models, studies of the impact of land surface variability on the predictability of climate, interactions between the terrestrial and atmospheric branches of the hydrologic cycle, and the impacts of land use change on regional and global climate. Dr. Dirmeyer is chair of the GEWEX Global Land-Atmosphere System Study (GLASS) and the GEWEX Global Soil Wetness Project (GSWP), a member of the interagency Global Water Cycle Panel (GWCP) Science Steering Group, the International Geosphere-Biosphere Programme (IGBP) Integrated Land Ecosystem-Atmosphere Process Study (ILEAPS) Scientific Steering Committee, and the American Meteorological Society (AMS) Committee on Hydrology.

B. E. Doty, B.S., Northern Illinois University, 1978. Associate Research Scientist, COLA. Mr. Doty develops data analysis and visualization systems for the scientific evaluation of large atmospheric and oceanic data sets. Mr. Doty has held positions in private industry as well as a research assistant position affiliated with Goddard Space Flight Center.

B. Huang, Ph.D., University of Maryland, 1992. Associate Research Scientist, COLA; Associate Professor, Climate Dynamics, George Mason University since September 2004. Dr. Huang conducts oceanic general circulation model experiments to study the seasonal and interannual variability of the tropical ocean circulation and to determine the sensitivity of the upper ocean currents and density structure to temporal and spatial variability of the atmospheric forcing (wind stress, total heat flux and fresh water flux) and to oceanic mixing processes. Dr. Huang also conducts ocean data assimilation experiments to provide the best possible ocean initial state for coupled predictions.

J. L. Kinter III, Ph.D., Princeton University, 1984. Director and Senior Research Scientist, COLA. Dr. Kinter directs all aspects of COLA research and administration, supervises a scientific, technical and administrative staff of 20 and serves as Director of the NOAA Applied Research Center at COLA. Dr. Kinter's research includes GCM experiments to understand predictability and prediction of Earth's climate, including the role of air-sea and air-land feedbacks, and improving simulation of the climate through model refinement. After completing his doctorate, Dr. Kinter was a National Research Council associate at NASA Goddard for one year, and assistant professor of meteorology (three years) and assistant research scientist (six years) at University of Maryland.

B. P. Kirtman, Ph.D., University of Maryland, 1992. Associate Research Scientist, COLA; Associate Professor, Climate Dynamics, George Mason University. Dr. Kirtman is working on the development of simple and complex coupled ocean atmosphere general circulation models, which are used to investigate the predictability of the coupled system on interannual to intraseasonal time scales, to study the influence of the tropics on mid-latitude predictability and to assess how the annual cycle affects intraseasonal and interannual predictability.

E. K. Schneider, Ph.D., Harvard University, 1976. Senior Research Scientist, COLA; Prof., Climate Dynamics, George Mason University. Dr. Schneider conducts research on dynamics of the climate system. After completing his doctorate, Dr. Schneider was a post-doctoral research associate at MIT for three years, a NATO post-doctoral fellow at University of Reading (England) for one year, a research fellow for three years and a research associate for two years at Harvard University, and a principal research scientist at MIT for one year. Dr. Schneider was an associate research scientist for six years and a senior research scientist for one year at University of Maryland.

P. Schopf, Ph.D., Princeton University, 1978. Professor of Oceanography, Associate Dean for Research, and Computing School of Sciences, George Mason University. Dr. Schopf conducts research on ocean dynamics and the dynamics of the coupled ocean-atmosphere system. He is the architect of the Poseidon Isopycnal Ocean Model. After completing his doctorate, Dr. Schopf was an assistant professor at Brown University for one year, and a physical oceanographer at NASA Goddard Space Flight Center for 19 years.

J. Shukla, Sc.D., MIT, 1976, Ph.D., BHU, 1971. President, IGES; Professor and Chairman, Climate Dynamics, George Mason University. Dr. Shukla conducts research on predictability of the coupled ocean-atmosphere-biosphere system, predictability of the tropical atmosphere, monsoon dynamics, reanalysis, deforestation and desertification. His research has shown that the influence of boundary conditions at the earth surface provides a physical basis for predictability of climate in the midst of chaos. He is author/coauthor of 150 scientific papers; 20 reports and book chapters; thesis adviser/coadviser for 16 Ph.D. students; chair/member of national and international scientific committees. He received the first Walker Gold Medal of the Indian Meteorological Society. He is a Fellow and recipient of the Rossby Research Medal of the American Meteorological Society and an Associate Fellow of the Third World Academy of Sciences. He is a member of the Joint Scientific Committee of the World Climate Research Programme. Dr. Shukla was affiliated with IITM, Poona, Princeton University, MIT, NASA Goddard, and the University of Maryland.

D. M. Straus, Ph.D., Cornell University, 1976. Senior Research Scientist, COLA; Professor, Climate Dynamics, George Mason University. Dr. Straus studies the dynamics and predictability of atmospheric motions on a wide range of time scales. He diagnoses coupled GCM dynamics using the models of COLA, NCAR, NCEP, GFDL, GSFC and ECMWF. Special interests include the properties of mid-latitude circulation regimes, and the influence of the extratropics on large-scale tropical motions. The large-scale divergent moist circulation and the fundamental instability and geostrophic turbulence properties of the atmosphere are being studied using the reanalyses of ECMWF and NCEP. After completing his doctorate, Dr. Straus was affiliated with MIT, NASA Goddard, and the University of Maryland.

Senior Scientific Staff

M. J. Fennessy, M.S., State University of New York (Albany), 1980. Research Scientist, COLA. Mr. Fennessy studies the impact of tropical and global boundary conditions on the predictability of the atmosphere on intraseasonal to interannual time scales. Prior to joining COLA, Mr. Fennessy was affiliated with NASA Goddard Space Flight Center.

V. Krishnamurthy, Ph.D., Massachusetts Institute of Technology, 1985. Senior Research Scientist COLA. Dr. Krishnamurthy conducts research on the variability and predictability of monsoon and on the application of theory of chaos and nonlinear dynamical systems for climate studies. After receiving his doctorate, he worked at MIT, University of Maryland and the International Centre for Theoretical Physics (Trieste).

L. Marx, M.S., Massachusetts Institute of Technology, 1977. Research Scientist, COLA. Mr. Marx studies a variety of atmospheric circulation problems, developing general circulation models and post processing/graphics systems to aid those investigations. Prior to joining COLA, Mr. Marx was affiliated with NASA Goddard Space Flight Center.

V. Misra, Ph.D., Florida State University, 1997. Research Scientist. Dr. Misra is conducting regional climate modeling studies over the South American region and coupled climate model development. Prior to joining COLA, Dr. Misra was associated with McGill University, Canada.

D. A. Paolino, M.S., University of Illinois, 1980. Research Scientist., COLA Mr. Paolino conducts analyses of atmospheric observations in both empirical studies and modeling efforts. Prior to joining COLA, Mr. Paolino was affiliated with NASA Goddard Space Flight Center.

Research Scientists

E. Altshuler, M.S., University of Maryland at College Park, 1996. Research Scientist, COLA. Mr. Altshuler is developing a desktop weather forecasting system, based on the NCEP Eta model, as part of a COLA/NWS collaboration to provide developing countries with the technology needed for short-range regional weather prediction. Prior to joining COLA, Mr. Altshuler was affiliated with the Department of Meteorology, University of Maryland at College Park.

B. Cash, Ph.D., The Pennsylvania State University, 2000. Research Scientist, COLA. Dr. Cash studies intra-seasonal variability and climate sensitivity using climate models and statistical methods. He also studies the links between climate and infectious diseases, particularly cholera. After completing his doctorate, Dr. Cash was a post-doctoral fellow at the Geophysical Fluid Dynamics Laboratory.

Z. Guo, Ph.D., Ohio State University, 2002; Ph.D. Institute of Oceanology, Chinese Academy of Sciences, 1998. Research Scientist, COLA. Dr. Guo works on land surface processes and their impacts on the weather and climate. Prior to joining COLA, Dr. Guo was affiliated with the Byrd Polar Research Center of Ohio State University.

Z.–Z. Hu, Ph.D., Peking University, 1991. Research Scientist, COLA. Dr. Hu conducts interannual and interdecadal climate variability and predictability studies. He is interested in the NAO, global warming and Asian monsoon studies and engaged in making multi-season predictions with coupled model. Prior to joining COLA, Dr. Hu was affiliated with Max Planck Institute for Meteorology, Germany.

R. Wu, Ph. D., University of Hawaii, 1999. Research Scientist, COLA. Dr. Wu is working on the monsoon-ENSO relationship and the role of air-sea interaction in climate variability through empirical study and numerical experiments.

Z. Wu, Ph.D., University of Washington, 1998. Research Scientist, COLA. Dr. Wu conducts theoretical research on large-scale atmospheric dynamics and performs numerical experiments with coupled models and observational data to improve understanding of climate dynamical processes and mechanisms for variability. Dr. Wu also works on the development of innovative data analysis methods and explores their applications to climate data. Prior to joining COLA, Dr. Wu was a Postdoctoral Fellow in JISAO at the University of Washington.

M. Zhao, Ph.D., Macquairie University, 2000. Research Scientist, COLA. Dr. Zhao's research focuses on the role of land surface processes in the climate system. She is involved in Dynamic Seasonal Prediction (DSP) project, which has the aim of understanding climate fluctuations on seasonal scale. She processes the data for ISLSCP-II and GSWP-II projects as well. Dr. Zhao is also an Honorary Associate of the Department of Physical Geography, Macquarie University.

Post-doctoral and Visiting Scientists

H.-K. Drbohlav, Ph.D. University of Hawaii, 2002. Post-doctoral Research Scientist, COLA. Dr. Drbohlav works on variability in the Indian Ocean region, including the northward propagating boreal summer intraseasonal oscillation, Indian Ocean zonal dipole mode, and seasonal (intraseasonal) monsoon predictability.

J. Manganello, Ph.D. George Mason University, 2004. Post-doctoral Research Scientist, COLA. Dr. Manganello studies interannual climate variability in the tropical Pacific and its interaction with the mean climate and the seasonal cycle. Her research interests also include low-frequency variability of the North Atlantic Oscillation.

D. Min, Ph.D., Texas A&M University, 2002. Post-doctoral Research Scientist, COLA. Dr. Min is interested in the seasonal to multi-decadal tropical sea surface temperature variability and developing the coupled ocean-atmosphere GCM.

C. Stan, Ph.D. Colorado State University, 2005. Post-doctoral Research Scientist, COLA. Dr. Stan's research interests lie in the area of climate variability. Her research activities include large-scale atmospheric dynamics on intra-seasonal time-scales and ocean-atmosphere interactions.

X. Yang, State University of New York at Stony Brook, 2006, Post-doctoral Research Scientist, COLA. Dr. Yang conducts original research on using initial tendency errors to reduce systematic errors in weather and climate forecast models and correct errors in such models.

Information Systems Staff

J. Adams, M.S., University of Washington, 1993. Research Associate, COLA. Ms. Adams develops new methods of analyzing and visualizing geophysical data. She documents and administers GrADS and the GrADS Data Server, maintains the data sets that are supported by the server, and provides technical support for the GrADS user community. Prior to joining COLA, Ms. Adams was affiliated with NOAA Pacific Marine Environmental Laboratory.

C. Steinmetz, Ph.D., Purdue University, 1991. Director of Information Systems and Computer Systems Analyst, COLA. Dr. Steinmetz manages all aspects of computer-server, file-server and web-server computer systems at COLA. Prior to joining COLA, Dr. Steinmetz was associated with the Indiana University.

T. Wakefield, Jr., B.S., University of Maryland University College, 2004. Systems Analyst. Mr. Wakefield provides computing, networking and information systems support for COLA's staff to meet their computing needs.

Adjunct Staff

E. Jin, Ph.D., Seoul National University, 2005. Adjunct Research Scientist, COLA. .; Research Assistant Professor, Climate Dynamics, George Mason University. Dr. Jin studies the dynamics and predictability of the climate system through both empirical studies and numerical experiments. She focuses on the seasonal predictability of the coupled system, the role of air-sea interaction in climate predictability, the ENSO-monsoon relationship, and the tropical influence on extratropical predictability. She is also involved in the CliPAS project, which is developing a well-validated multi-model ensemble system for climate prediction and its application to society, in collaboration with the Asia-Pacific Climate Center.

B. Klinger, Ph.D., Massachusetts Institute of Technology Woods Hole Oceanographic Institution, 1992. Adjunct Research Scientist, COLA; Associate Professor, Climate Dynamics, George Mason University. Dr. Klinger uses numerical and analytical models to conduct research on ocean dynamics, especially aspects that are relevant to climate. Recent topics of interest include the thermohaline circulation, analysis of oceanic heat transport, and decadal variability in the Pacific. Prior to working with COLA, Dr. Klinger was affiliated with Nova Southeastern University.

7.2 Scientific Advisory Committee

The Scientific Advisory Committee (SAC) was formed to examine COLA's research activities, provide guidance and recommendations for future work, and to render its professional judgment about the quality and importance of COLA research contributions. The SAC meets three times in each five-year period to review all COLA scientific activity.

The COLA Director provides an Annual Report to document milestones and major achievements, positive actions taken in response to prior SAC recommendations, personnel changes, major procurements, and any changes in the scope of COLA scientific projects each year. A five-year Science Review (this document) is provided at the mid-point of the COLA funding cycle to provide a longer-term perspective on accomplishments. The SAC reports its evaluations of the current state of COLA research, and its recommendations for the future to the President of IGES, who transmits the report to representatives of the federal funding agencies.

The SAC includes internationally recognized climate scientists from universities, federal research laboratories, and non-profit research institutes. Members of the SAC are nominated by the President of IGES for three-year terms in consultation with the Principal Investigators of COLA. The COLA SAC membership is determined in consultation with the representatives of the federal funding agencies. During the period of this report, the SAC met in February 2002, February 2003, and September 2005, and its membership included:

D. Anderson, European Centre for Medium-Range Weather Forecasts (2005 -)
G. Branstator, National Center for Atmospheric Research (1999 -)
D. Burridge, European Centre for Medium Range Weather Forecasts (2001 – 2005)
R. Dickinson, Georgia Institute Of Technology (1998 - ; chair, 2004 -)
D. Hartmann, University of Washington (1998-2005; chair, 1999-2003)
A. Leetmaa, Geophysical Fluid Dynamics Laboratory, NOAA (2000 – 2005)
G. North, Texas A&M University (1999 – 2005)
S. Schubert, NASA Goddard Space Flight Center (2002 -)
J. Slingo, University of Reading (U.K.; 2005 -)
S. Soorooshian, University of California at Irvine (2005 -)
B. Wang, University of Hawaii (2005 -)

In it's most recent meeting (September 2005), the COLA SAC found that "…the current programs at COLA are of uniformly high quality and that they are 'right on target' in terms of the directions indicated in their previous five-year proposal." They also noted that, "The quality and quantity of [COLA's] research publications continues to be very impressive." The SAC report noted that COLA's "remarkable effectiveness" results from a tightly coherent staff working toward common goals, which "… depends on the multi-agency form of the funding [COLA] receives, the abilities of NASA, NSF, and NOAA program managers to collectively provide such funding, and COLA's modest size and continuity of staff."

The SAC focused its attention on the multi-model research effort, which they felt has "… strong enough promise to warrant major investments in COLA's efforts." The extension of the interactive ensemble approach to multiple models was deemed promising. The SAC expressed concern that COLA's use of too many models could stretch resources too thinly, especially plans to incorporate multiple ocean models. The recommendation made by the SAC was for "… advanced planning at the tactical level to be able to match chosen activities to computational and human resources available without threatening a loss of parallel and perhaps equally important activities." The SAC suggested that such planning might include partnering with likely beneficiaries of the interactive ensemble methodology, limiting further investment in the COLA model, limiting the outside models to no more than three and only including those with strong outside support for which collaborative arrangements would be relatively easy to implement. The SAC felt that COLA, in working with multiple models from the major US centers, including the CCSM, CFS, GFDL and NASA-GMAO models, would "…uniquely fill a valuable niche to lend major support to the advancement of climate and NWP modeling." In particular, the SAC expects COLA to establish the aspects of the major models are *not* working well enough for the purposes of seasonal climate prediction.

In terms of planning for the future, the SAC recommended that a yearly implementation plan be prepared to focus and prioritize activities leading up to the next five-year COLA omnibus proposal. The SAC suggested that COLA should address emerging issues in predictability and the interface with climate change, including, for example, the role of the stratosphere in seasonal to decadal predictability and modes of decadal predictability.

The Director and all members of the COLA scientific and technical staff were extremely gratified by the praise of COLA's activities and strongly agreed with the SAC's assessment that the success of COLA over the years has been due in no small part to the multi-agency funding provided collectively by NSF, NOAA and NASA. COLA scientists also expressed their gratification with the SAC's commendations for the land surface modeling activity and the information systems work. It has long been the view at COLA that land-atmosphere interactions are an essential component of seasonal climate predictability. COLA has also had a long-standing commitment to developing and supporting GrADS, which has from time to time had external funding, but has for the most part been supported within the omnibus framework.

Following the receipt of the SAC report, the COLA Executive Committee held a series of meetings in October and November 2005 to discuss strategy to take advantage of the SAC's expert advice. In particular, the multi-model strategy and the future of the COLA model were the main areas of discussion. It was agreed that COLA would adopt a "National models" approach, in which the models being fully supported by the major modeling centers of NSF, NOAA and NASA would be the principal tools to be used for multi-model evaluation of seasonal to decadal predictability. As such, it was decided that the COLA model would cease to be a model under active refinement, although it would continue to be used in projects that were already underway, notably the evaluation of remote vs. intrinsic predictability in the Atlantic and Indian Ocean regions, and the quantification of the contribution of land surface variations to seasonal predictability. A full evaluation of the performance of the COLA model, suitably tuned in coupled ocean-atmosphere mode, was completed and a series of papers was submitted for publication.

Also immediately after the COLA SAC met, the World Climate Research Program (WCRP) Modeling Panel (WMP) held its first workshop in October in Exeter, U.K. The workshop addressed the issue of seamless weather and climate prediction from days to decades. Three approaches emerged from that meeting: testing numerical weather prediction models for seasonal prediction; confronting models used in the Intergovernmental Panel on Climate Change (IPCC) assessments with real initial conditions for seasonal prediction; and model development toward explicit representation of processes, in particular, convective clouds. COLA had been a pioneer in the first approach, having adopted the NWP model in use at the NOAA National Meteorological Center (NMC; now NCEP) for use as a climate predictability research tool in 1985. The COLA Executive Committee agreed that the second approach would be quite suitable for conducting its multi-model predictability research and decided to consider one or more IPCC-class models in its multi-model ensemble.

Among the National models to be used, the Community Climate System Model (CCSM) and the Climate Forecast System (CFS) of the National Centers for Environmental Prediction (NCEP), were immediately selected. The CCSM is an IPCC-class model with a large community of users, a robust support infrastructure hosted at the National Center for Atmospheric Research (NCAR), and a large archive of control runs in various configurations. The CFS is routinely used for seasonal climate prediction by NCEP, and it is the centerpiece of the new NOAA Climate Test Bed (CTB), for which ample support resources were recently deployed at NCEP.

The SAC's recommendation for COLA to undertake a strategic planning exercise was also taken up by the COLA Executive Committee. A series of meetings was held in 2006 to begin consideration of organizational and research content issues for COLA's principal activities in the 2009-2013 period.

7.3 Service To Community

7.3.1 Educational Activities (GMU/COLA)

COLA scientists consider the education of the next generation of climate modelers to be critical to the advancement of our science and the improvement of our understanding of the variability and predictability of the Earth's climate. Several COLA scientists hold joint appointments as faculty members of George Mason University (GMU), Fairfax, Virginia. In addition to the program with GMU, COLA scientists maintain a strong link with other educational institutions, including the International Centre for Theoretical Physics (ICTP; Trieste, Italy), the University of Seoul (South Korea) and Allahabad University (India).

George Mason University Climate Dynamics Program

COLA maintains a Joint Doctoral Program with the School of Computational Sciences (SCS) of GMU (www.scs.gmu.edu/climate/climate_phd.html) offering a Ph.D. in Climate Dynamics since 2003. J. Shukla, who holds a joint appointment as full professor at GMU, is chair of the program. The faculty of the Joint Doctoral Program include T. DelSole, B. Huang, P. Houser (Director of the newly-established Center for Research on Environment and Water), B. Kirtman, B. Klinger, E. Schneider, P. Schopf, who is also associate dean of SCS, J. Shukla, and D. Straus. J. Kinter is a part-time faculty member. In addition, P. Dirmeyer, R. Koster (NASA Goddard), V. Krishnamurthy, and Y. Sud (NASA Goddard) are part-time lecturers in the program. The Program offers a full curriculum of core courses leading to the Ph.D. degree. Students enrolled in the program are provided with office space and access to all facilities at COLA, and they interact with COLA scientists on a daily basis, participating fully in COLA research. The collocation of the students at COLA has engendered an active Journal Club, which provides stimulating discussion of current and emerging topics among students, faculty and COLA staff.

Graduates, with their graduation year, current position and thesis title include:

Anjuli Bamzai (1997)	DOE Headquarters (program manager) Observational and Modeling Study of Snow and Its Relation to the Indian Summer Monsoon
Mary Ellen Verona (2002)	(deceased) Observational Analysis and Numerical Simulation of 1997-1998 El Nino
Julia Manganello (2004)	COLA (post-doctoral associate) The Influence of Sea Surface Temperature Anomalies on Low-Frequency Variability of the North Atlantic Oscillation
Whit Anderson (2004)	NOAA GFDL (post-doctoral associate) Oceanic Sill - Overflow Systems: Investigation and Simulation with the Poseidon Ocean General Circulation Model
Rob Burgman (2005)	University of Miami (post-doctoral associate) ENSO Decadal Variability in a Tropically-Forced Hybrid Coupled Model
Yuri Vikhliaev (2005)	NASA Goddard (post-doctoral associate) Decadal Extra-Tropical Pacific Variability
Susan Bates ('06)	University of Washington (post-doctoral associate) The Role of the Annual Cycle in the Coupled Ocean-Atmosphere Variability in the Tropical Atlantic Ocean
Laura Feudale ('06)	International Centre for Theoretical Physics (post-doctoral associate) Extreme Events in Europe and North America During 1950-2003: An Observational and Modeling Study

In 2006, 16 graduate students were enrolled in the program. They include (with their academic advisors): D. Achuthavarier (Krishnamurthy), K. Arsenault (Dirmeyer/Shukla), C. Cruz (Klinger), M. Fan (Schneider), X. Feng (Houser), Y. Jang (Straus), L. Jia (DelSole), D. Jin (Kirtman), N. Jyothi (Shukla), L. Krishnamurthy (Shukla), J. Li (Huang), B. Narapusetty (Kirtman), V. Nolan (Shukla), X. Pan (Shukla; anticipated graduation 2007; thesis: Predictability and Prediction of Tropical Seasonal and Interannual Ocean and Atmosphere Variability in CCSM3), K. Pegion (Shukla; anticipated graduation 2007; thesis: Potential Predictability of Tropical Intraseasonal Variability in the NCEP Climate Forecast System), and E. Swenson (Straus).

Intern Program

The COLA Summer Intern program provides an opportunity for talented high school and college students with an interest in climate research to spend a summer (8-12 weeks) participating in activities that are undertaken as part of the basic and applied research program at COLA. Each intern works with a COLA staff scientist/supervisor who devises the work plan for that student's project. Upon completion of the project, each intern prepares a short report documenting his or her work, which is evaluated by the supervisor.

In 2004, COLA had one high school intern, named Jeffrey Dunn, from Montgomery Blair High School in Silver Spring, MD. Jeff worked with Paul Dirmeyer on a project that contributed to the Global Soil Wetness Project 2. Jeff prepared his results as a submission to the Intel Science Talent Search competition (http://www.sciserv.org/sts/), and he was selected as a Semi-Finalist (http://www.sciserv.org/sts/press/20050112.asp).

In 2005, four students came to COLA as interns. Two students were from Montgomery Blair High School in Silver Spring, MD. Brett Holbert worked with P. Dirmeyer on a project that contributed to the Global Soil Wetness Project, and Yuning Zhang worked with V. Misra on an assessment of the predictability of precipitation over Nordeste, Brazil, in the NCEP CFS hindcasts. Samuel Gilman, from SUNY in Albany, NY worked with D. Straus on chaos and regimes, and Jerome Reese from Saginaw High School in Saganaw, MI worked with B. Kirtman on consolidating data from the SMIP experiment.

In 2006, four students participated in the COLA intern program. They were Emily Huang from Centennial High School in Ellicott City, MD, Vince Agard and George Moomau from Montgomery Blair High School, and Eric Swenson from St. Cloud University, St. Cloud, MN. Emily worked with M. Zhao on the quality of diverse soil moisture analyses. Vince worked with B. Huang on the role of Atlantic and Caribbean SST in hurricane intensification. George worked with V. Misra to examine the skill of coupled models in predicting hurricane-like conditions. Eric did a project on the index of refraction in atmospheric flows with D. Straus, and he joined the GMU Ph.D. program in Climate Dynamics at the end of the summer.

7.3.2 Lectures and Seminars

The **COLA Distinguished Visiting Lecturer** series brings the foremost experts in the field to visit COLA and describe recent work of interest. Also, from time to time, scientists have visited COLA to provide lectures or engage in collaborative discussions. A list of these visitors, in chronological order during the reporting period, follows:

2002:

Claire Perigaud, JPL California Inst. Technology, *The Role of the Salinity-Precipitation Anomalies in the Halo-Thermo-Dynamic Processes of the 1992-2000 Events of the Indian Ocean/Atmosphere* (February 7, 2002)

Suki Manabe, Princeton University, *Hydrologic Change Associated with Global Warming* (March 8, 2002)

Doron Nof*, Florida State University,* Is There a Meridional Overturning Cell in The Pacific Ocean? *(March 14, 2002)*

Bin Wang, University of Hawaii, *Coupled Monsoon-ocean Mode and its Impact on the Asian-Australian Monsoon Variation* (April 19, 2002)

Tapio Schneider, California Inst. Technology, The Tropopause and the Thermal Stratification of the Extratropical Atmosphere (May 6, 2002)

Hans von Storch, Inst. of Coastal Research (Germany), *Issues in Regional Atmospheric Modeling: Large Scale Control and Divergence in Phase Space* (May 24, 2002)

Fei-Fei Jin, University of Hawaii, Understanding ENSO Beyond a Simple Oscillator Paradigm (August 6, 2002)

Julia Slingo, (Director) Center for Global Atmospheric Modeling, University of Reading (UK), *Scale Interactions on Diurnal to Seasonal Timescales: Their Relevance to Seasonal Predictability and Model Systematic Error* (September 30, 2002)

Lennart Bengtsson, Max-Planck-Institute, Hamburg (Germany)**,** *Predictability of the North Atlantic Oscillation* (October 9, 2002)

Brian Hoskins, University of Reading (UK), *Summer Monsoons, Subtropical Anticyclones and European Floods.* (October 16, 2002)

K. R. Sreenivasan, University of Maryland (now at ICTP, Trieste, Italy), *Turbulent Convection* (November 12, 2002)

Harshvardhan, Purdue University, *Retrieval of Microphysical and Thermodynamic Properties From Non-Uniform Cloud Fields* (November 13, 2002).

2003:

Donald R. Johnson, University of Wisconsin**,** *Analysis and Modeling of Weather and Climate Globally Employing Isentropic Perspectives* (January 29, 2003)

In-Sik Kang, (Director) Climate Environment System Research Center, Seoul National University (South Korea), *Potential Predictability of a Dynamical-Statistical Seasonal Prediction System* (February 21, 2003)

Clemente Tanajura, LNCC (Brazil), *A Data Assimilation Method Based on the Fokker-Planck Equation and it's Application in the Tropical Oceans* (Februaury 24, 2003)

Shuanglin Li, NOAA/CDC, *The Nonlinearity, Seasonal-Dependence of Atmospheric Response to the North Atlantic SST Tripole* (March 10, 2003)

Christos Mitas, University of Illinois at Urbana-Champaign, *A Linear Instability Analyses of Generalized Barotropic Operators* (March 17, 2003)

Duane Waliser, SUNY Albany, *Simulating and Predicting Tropical Intraseasonal Variability* (April 11, 2003)

Marvin Geller, (Dean and Director) Marine Sciences Research Center, SUNY Stonybrook, *Stratospheric Water Vapor and the Tropical Tropopause* (May 12, 2003), *Gravity Wave Parameters Derived from U.S. High Resolution Radiosonde Data* (May 13, 2003)

Syukuro Manabe, Princeton University, *Reducing Feedback Uncertainty in Climate Models* (June 2, 2003)

Andrea Hahmann, University of Arizona, *Representing Spatial Sub-Grid Variability At The Land-Atmosphere Interface In A GCM* (June 5, 2003)

Claudio Cioffi-Revilla, George Mason University, *Record Warfare in the Global System and the Next Magnitude μR > 7.1, Record-setting Conflict: A Preliminary Analysis and Biospheric Implications* (October 20, 2003)

Lennart Bengtsson, Max Planck Institute, Hamburg (Germany**),** *Can Climate Trends be Calculated from Re-Analysis Data?* (November 10, 2003)

Kazuaki Kawamoto, RIHN (Japan), *Possible Influence of the Anthropogenic SO2 Emissionon Low-Level Cloud Properties Over China* (December 4, 2003)

Wanqiu Wang, NOAA Environmental Modeling Center, *Seasonal and Intraseasonal Prediction Efforts at NCEP: Toward a Seamless Suite of Forecast Products* (December 9, 2003)

Elisa Manzini, Istituto Nazionale di Geofisica e Vulcanologia (Italy), *Interactive Climate Chemistry Modelling:Implications for Recent Stratospheric Cooling* (November 3, 2003)

2004:

Jiayu Zhou, NOAA National Weather Service, *NWS Science and Technology Infusion Plan for Climate Services - Bridging Climate Research and Operations* (January 20, 2004).

Menas Kafatos and colleagues, George Mason University, *Regional Effects of Climate Phenomena and the Role of Remote Sensing (*March 9, 2004)

Shuhua Li, NASA Goddard Space Flight Center, *NASA GEOS-4 Reanalysis: Assessment and a Sensitivity Study* (March 10, 2004)

Qing Liu, Georgia Institute of Technology, *Improving the Parameterizations of Soil Properties and Land Ecosystems for Modeling Climate* (March 30, 2004)

Andy Majda, Courant Institute of Mathematical Sciences, *Systematic Strategies for Stochastic Climate Models (*April 12, 2004)

Thomas Reichler, NOAA Geophysical Fluid Dynamics Laboratory, *The Role of Initial and Boundary Conditions for the Time-Space Distribution of Sub-seasonal Atmospheric Predictability* (May 10, 2004)

Craig Collier, Texas A&M University, *The Diurnal Cycle of Tropical Precipitation in a General Circulation Model* (May 12, 2004)

Yimin Ma, George Mason University, *Recirculation of Coastal Urban Air Pollution Under a Synoptic Scale Thermal Trough in Perth, Western Australia* (May 13, 2004)

Dick Valent, National Center for Atmospheric Research, *NCAR/SCD Computer Changes* (May 18, 2004)

Ian Jolliffe, University of Aberdeen**,** *Forecast verification – did we get it right?* (June 7, 2004),
To Center or not to Center... Or Perhaps Do It Twice? (June 8, 2004)

Gilbert P. Compo, NOAA Climate Diagnostic Center, *Storm Track Predictability on Seasonal to Decadal Scales* (June 29, 2004),
Feasibility of a Reanalysis Using Only Surface Data (June 30, 2004)

Song Yang, NOAA Climate Prediction Center, *Interannual Variability of the Asian-Australian Monsoon* (October 6, 2004)

Cort J. Willmott, University of Delaware, *On the Use of Dimensioned Measures of Average Error in Comparing Climate Fields* (November 1, 2004)

Shu-Chih Yang & Eugenia Kalnay, University of Maryland, *ENSO Bred Vectors in Coupled General Circulation Models for ENSO Prediction* (December 14, 2004)

2005:

Sumant Nigam, University of Maryland, *Warm-season Hydroclimate Variability Over the Great Plains in*

Observations, Reanalysis and Atmospheric Model Simulations (January 19, 2005)

Peitao Peng, NOAA Climate Prediction Center, *Variability, Predictability and Prediction of DJF Climate in NCEP Coupled Forecast System (CFS)* (February 3, 2005)

Stephen Dery, NOAA/GFDL, *Investigating the Water Budget of Canada's Hudson Bay Basin* (February 28, 2005**)**

Ming Cai, Florida State University, *Dynamical Amplifier of the Global Warming due to Anthropogenic Greenhouse Gases and Thermodynamical Feedbacks* (March 8, 2005)

Long Chiu, George Mason University, *Variations of Oceanic Evaporation from Remote Sensing Data Sets* (March 31, 2005)

Yu-Tai Hou, NOAA/NCEP, *Building a New Radiation System for GCM Applications* (April 18, 2005)

Melvyn Shapiro. NOAA, *Prediction of High Impact Weather From Minutes to Millenia* (April 19, 2005)

Xiaogu Zheng, NIWA (New Zealand), *A Study of Predictable Patterns for Seasonal Forecasting of New Zealand Rainfall* (May 31, 2005)

H. Annamalai, University of Hawaii, *Regional Heat Sources And The Active/Break Phases Of The Summer Monsoon* (June 24, 2005)

Michael Tippett, International Research Institute, Columbia University, *Potential Predictability, Ensemble Forecasts And Tercile Probabilities* (June 30, 2005)

Magdalena Balmaseda, European Centre for Medium-Range Weather Forecasts, *The New ECMWF Seasonal Forecast System* (September 7, 2005)

David Randall, Colorado State University, *Counting the Clouds* (September 13, 2005)

Syukuro Manabe, Princeton University, *ENSO in a Coupled Ocean-Atmosphere Model: Amplitude Modulation and CO2 Sensitivity* (October 11, 2005)

Hans von Storch, Institute of Coastal Research (Germany), *Hockey Sticks, the Tragedy of the Commons and Sustainability of Climate Science* (October 20, 2005)

Tom Delworth, NOAA Geophysical Fluid Dynamics Laboratory, *Simulation of 20th Century Climate Change in the GFDL Coupled Models* (November 30, 2005)

Leonard Smith, Oxford University (U.K.), *Betting On The Forecast: Methods For Risk Management, Information Identification and Resource Allocation in an Ensemble Weather* (December 14, 2005)

2006:

Peter J. Webster, Georgia Institute of Technology, *Hurricanes in a Warming World: From Genesis to Revelation* (January 13, 2006)

Michelle L'Heureux, NOAA Climate Prediction Center, *Observed Relationships Between the El-Niño/ Southern Oscillation and the Extratropical Zonal-Mean Circulation* (January 25, 2006)

Kikuro Miyakoda, Princeton University, *ENSO Oscillation and the Decadal Variation* (March 17, 2006)

Donald Johnson, NCEP Special Project Scientist and Prof. Emeritus, University of Wisconsin, *The Relevance of Entropy in Modeling and Studies of Weather and Climate: Lessons We Should Have Learned Had We Paid Attention in School* (March 29, 2006)

Antonio J. Busalacchi, (Director) Earth System Science Interdisciplinary Center, University of Maryland, *Climate and Ecosystem Variability: Forcings and Feedbacks: 2006 AMS Walter Orr Roberts Interdisciplinary Science Lecture* (April 4, 2006)

Lisa Goddard, The International Research Institute for Climate and Society, Columbia University, *Towards Prediction of the Full Probability Distribution of Seasonal Climate* (May 9, 2006)

Donglian Yuan, Institute of Oceanology, Chinese Academy of Science, *Roles of the equatorial waves and western boundary reflection in the seasonal circulation of the equatorial Indian Ocean* (May 18, 2006)

Antonio Navarra, Istituto Nazionale di Geofisica e Vulcanologia (Italy), *The Euro-Mediterranean Center on Climate Change: a New Italian Initiative* (May 31, 2006)

Liqiang Sun, The International Research Institute for Climate and Society, Columbia University, *Climate Downscaling: The Value Added Using Regional Dynamical Models* (June 9, 2006)

Louis Uccellini, (Director) NOAA National Centers for Environmental Prediction, *NCEP Update: Review of Progress in Operational Weather, Climate and Ocean Forecasts* (June 20, 2006)

Yogesh Sud, NASA Goddard Space Flight Center, *Problems and Prospects of Simulating Aerosol-cloud-radiation Interaction for Water, Mixed Phase, and Ice Clouds in GCMs* (June 23, 2006)

Mike Harrison, Hadley Center, Met Office (UK), *Development in Africa - a view on the role and improvement of seasonal predictions* (June 27, 2006)

Q. C. Zeng, Institute of Atmospheric Physics, Chinese Academy of Sciences, *Dust Storm, the Mechanism of Dust Emission and their Predictions* (July 17, 2006)

Lai-Yung (Ruby) Leung, Pacific Northwest National Laboratory, *Regional Climate Modeling: Recent Development and Applications* (August 4, 2006**)**

Jialin Lin, NOAA Climate Diagnostics Center, *Understanding the Tropical Biases in GCMs: Double-ITCZ, ENSO, MJO and Convectively Coupled Equatorial Waves* (13 October 2006)

William Lau, (Chief) Laboratory for Atmospheres, NASA Goddard Space Flight Center, *Aerosol-monsoon rainfall interaction: the role of the Tibetan Plateau* (29 November 2006)

7.3.3 Workshops

2nd Int'l. Climate of the 20th Century Workshop (22-25 January 2002) COLA

The second international Climate of the 20th Century (C20C) workshop was held 22-25 January 2002 at COLA. The goal of the workshop, organized by C. Folland of the Hadley Centre (U.K.) and J. L. Kinter III of COLA, was to review progress and particularly to plan a more highly structured C20C project. The workshop was held just before a World Meteorological Organization (WMO) Global Climate Observing System (GCOS) Workshop on Advances in the Use of Historical Marine Climate Data (29 Jan - 1 February 2002), chaired by Folland (co-organizer of C20C), so that participants could communicate their ideas about further improvements to SST and sea ice data sets that might be used by C20C. More information is contained at www.iges.org/c20c/workshop2002.

Land Information System Workshop (4 March 2002 and 21 January 2003) COLA

The Land Information System (LIS) is a collaborative research project, supported by NASA, that enhances land surface modeling research by providing appropriate input data to select land surface models, and outputting data in a readily usable form. Land surface models seek to predict the terrestrial water, energy and biogeochemical processes by solving the governing equations of the soil-vegetation-snowpack medium. In order to predict water, energy and biogeochemical processes using (typically 1-D vertical) partial differential equations, land surface models require initial conditions, boundary conditions, and parameters. Output from the land surface models translates to variables in ALMA standard format such as soil moisture, surface runoffs, and canopy conductance. A series of workshops was hosted by COLA to initiate the collaboration and bring partners together to communicate progress and plan next steps. A web site describing the outcome of the project is at http://lis.gsfc.nasa.gov/.

GEWEC Workshop (30 September - 1 October 2002) COLA

On 30 September – 1 October 2002, COLA hosted the kick-off meeting for the second phase of the Global Soil Wetness Project (GSWP-2), which is an ongoing environmental modeling research activity of the Global Land-Atmosphere System Study (GLASS) and the International Satellite Land-Surface Climatology Project (ISLSCP), both contributing projects of the Global Energy and Water Cycle Experiment (GEWEX). The goals of GSWP are to:

- Produce state-of-the-art global data sets of land surface fluxes, state variables, and related hydrologic quantities.
- Develop and test large-scale validation, calibration, and assimilation techniques over land.
- Provide a large-scale validation and quality check of the ISLSCP data sets.
- Compare Land Surface Schemes (LSSs), and conduct sensitivity studies of specific parameterizations and forcings, which should aid future model and data set development.

GSWP-2 is closely linked to the ISLSCP Initiative II data effort, and LSS simulations in GSWP-2 will encompass the same core 10-year period as ISLSCP Initiative II (1986-1995).

The kick-off meeting provided an opportunity to bring together the five basic categories of participants in GSWP-2: the operational centers, the land-surface modelers, validators of the model output, those involved in remote sensing applications, and other users of the model output.

A major product of GSWP-2 will be a multi-model land surface analysis for the ISLSCP Initiative II period. Further information about the project is provided on the web site: http://www.iges.org/gswp/.

27th Climate Diagnostics & Prediction Workshop (22-25 October 2002) GMU

The 27th Climate Diagnostics and Prediction Workshop was held on 21-25 October 2002 at George Mason University, Fairfax, Virginia. The workshop was co-hosted by the Climate Prediction Center of the National Centers for Environmental Prediction (NCEP)/NOAA, Washington, D.C., and COLA. The American Meteorological Society was a cooperating sponsor. The workshop (http://www.iges.org/cdpw/), organized by Wayne Higgins of NCEP and J. L. Kinter III of COLA, covered a variety of topics, including a review and assessment of recent climate anomalies; defining, diagnosing and predicting El Nino and its impacts; diagnosing and predicting global and regional monsoon characteristics and associated teleconnections on intra-seasonal (MJO), inter-annual (ENSO) and inter-decadal time scales; diagnosing and predicting AO, NAO, PDO, PNA and the links between climate variability associated with these modes and extreme weather events; and experimental long-lead prediction on the monthly, seasonal, inter-annual and inter-decadal time scales (skill, methodology, etc.). Interestingly, the workshop, which took place during the rampage by the Washington-area snipers, was disrupted on its second day by a metro-wide dragnet. The snipers were apprehended on 24 October, the fourth day of the workshop.

US-India Science Workshop (16-18 December 2002) COLA

The U.S. and India have a bilateral agreement on science and technology that includes projects on weather and climate. There has been a long-standing interest on the part of scientists at COLA to enhance the weather and climate prediction capabilities in India, where the monsoon and its fluctuations are of such vital importance to the livelihoods and security of the people and country of India. Also, there has been keen interest in integrating the data from the Indian weather satellite (INSAT) into the global observational data sets that are routinely used for weather and climate research. COLA hosted a gathering of Indian and U.S. scientists on 16-18 December 2002 for the purpose of furthering the bilateral research discussions. Much of the material that was discussed was later raised at a meeting of ministers.

Sloan: Predictability of Weather (17-19 February 2003) Savannah, GA

The Alfred P. Sloan Foundation sponsored a workshop on "The Known, the Unknown and the Unknowable in Weather Predictability," held on 17-19 February 2003 in Savannah, GA. This workshop was jointly organized by D. M. Straus, J. Shukla and B. P. Kirtman of George Mason University and COLA. The participants, including many of the most respected experts in weather predictability, met and engaged in both detailed and broad discussion of weather prediction and predictability in the present and future. Even nature attempted to attend the workshop: a snowstorm of record-breaking proportions shut down the Washington DC area before and during the workshop, disrupting travel plans and forcing the use of remote speaker-phone / e-mailed Power Point presentations!

Jesse Ausubel, representing the Sloan Foundation, opened the workshop by noting that it is very helpful in many fields to review what is known and what is unknown. In the natural sciences in particular, some things are just too large to know (e.g. require too much data or too much computation), while others are truly unknowable. Understanding what we know and don't know, how to move that boundary, and what component of what is unknown is in fact knowable are all very helpful activities to both scientists and to society at large.

3rd Int'l. Climate of the 20th Century Workshop (19-22 April 2004) ICTP

The third workshop of the International Climate of the 20th Century (C20C) project was held on 19-22 April 2004 at the International Centre for Theoretical Physics (ICTP) in Trieste, Italy. The workshop was organized by COLA, the Hadley Centre (U.K.), and the Physics of Weather and Climate section of ICTP. The results of SST-forced AGCM experiments run by the 15 C20C modeling groups were presented along with results from a subset of the models with other forcings (greenhouse gases, volcanic aerosols, solar variations, etc.). Discussions of how to evolve the C20C project into a coupled ocean-atmosphere context and how to align the goals of the C20C project with the WCRP Working Groups on Coupled Modeling and Seasonal to Interannual Prediction were undertaken.

The complete program of the workshop, including presentations by the speakers, is available at www.iges.org/c20c/workshop2004.

COLA 20th Anniversary Symposium (18 June 2004) COLA

The Symposium on Climate Dynamics and Predictability was held on Friday, 18 June 2004 at the Sheraton College Park, adjacent to the COLA office building in Calverton, Maryland to celebrate the 20th anniversary of the founding of the Center for Ocean-Land-Atmosphere Studies (COLA).

The symposium was held to mark the founding of COLA in 1984, when several scientists formed the core research group with that name at the University of Maryland at College Park. In the 20 years since it was established, COLA has made several contributions to our understanding of the predictability of seasonal atmospheric variations, the predictability of interannual ocean-atmosphere variations, the interactions between the land surface and climate, the variability of monsoons, reanalysis of atmospheric and oceanic observations, fundamental climate dynamics and scientific leadership of the national and international climate research communities. The 20th anniversary symposium reviewed the status of those areas in which COLA has contributed, and provided a glimpse of the prospects for further advancement in those areas.

A complete program and photos of the event may be found at http://www.iges.org/cola20/.

Sloan Workshop, Montreal (September 6-10, 2004) Montreal, Quebec

The workshop on Weather Variability in a Changing Climate: The Known, the Unknown and the Unknowable, was held on 8-10 September 2004 in Montreal, Canada. The workshop, sponsored by the Sloan Foundation, George Mason University and COLA, was organized by J. Shukla, David Straus and Ben Kirtman.

The workshop focused on the impacts of climate change on weather variability as opposed to projections of climate change, although the workshop included a broad overview of what is known regarding climate change. The reason for the focus on weather variability is based on how consumers of information use weather data. For example, to the typical "person-on-the-street," climate change or global warming is presented as a 2-4 degree change in the global mean temperature. This is essentially meaningless to the person-on-the-street – it cannot be used for planning or mitigation strategies. On the other hand, if the person-on-the-street knows that in the current climate that there will be somewhere between three and seven major winter storms and that in a global warming scenario this probability shifts to somewhere on the order of seven to fifteen storms, then risk assessments, mitigations and planning can respond accordingly. Similar arguments can be made for heat waves, cold spells, droughts, floods, hurricanes, tropical cyclones, among other weather extremes.

The workshop assessed what is known, unknown and unknowable about changes in the distribution of weather in a changing climate. Questions addressed in the workshop included: Is there evidence for changes in the variability or extremes based on the current observational records? What are the observational impediments? What cannot be determined from observational data? The workshop will also assess of the current status of climate change models and their projections of climate change. What is known and unknown about model based projections for changes in weather variability? What aspects of changes in weather variability are unknowable based on model projections? What are the abilities and limitations of the current climate change models? Are the model-based projections consistent with observations?

The 1st CliPAS Workshop (CliPAS-1; 5-6 May 2005**)** COLA

The first working meeting of the US-Korea joint project in support of the Asic-Pacific Climate Center (APCC) on Climate Prediction and its Application to Society (CliPAS) was held at COLA on 5-6th May, 2005. CliPAS is sponsored by the Korean Meteorological Administration (KMA). About 20 participants from 7 institutes attended the meeting.

CliPAS-1 participants reviewed the CliPAS project objectives. Participants exchanged information about their climate modeling and prediction activities in discussions that were effective and productive. The discussions were focused on the following themes: (1) Multi-Model Ensemble (MME) seasonal predictions; (2) Multi-institutional Historical Forecast Project (HFP) data production for the APCC Multi-Model Ensemble System; (3) Coupled model initialization and data assimilation; (4) Subseasonal prediction; (5) Multi-model interactive ensemble forecast system; and (6) Implementation of the CliPAS project plan.

Climate of the 20th Century Interim Workshop (4-6 July 2005)) Prague, Czech Rep.

The International Climate of the 20th Century (C20C) project held a joint workshop with the World Meteorological Organization (WMO) World Climate Research Programme (WCRP) Working Group on Seasonal to Interannual Prediction (WGSIP) on 4-6 July 2005 at the Hotel Krystal in Prague, Czech Republic. The workshop was organized by COLA (J. Kinter), the Hadley Centre (U.K.; C. Folland), and WGSIP (B. Kirtman), and hosted by the MAthematical Geophysics, Meteorology, and their Applications (MAGMA; T. Halenka) project of the Charles University of Prague (est. 1348), which is funded under the European Union's Fifth Framework Programme for support to Newly Assisted States. The workshop web page is http://www.iges.org/c20c (*July 2005 Workshop*).

The goal of the Prague workshop was to define, implement and analyze collaborative numerical experiments in two areas. The first was a series of "pacemaker" experiments in which tropical Pacific SST is prescribed from observations, but coupled air-sea feedbacks are maintained in the other ocean basins (e.g. Lau and Nath, 2003). The second area was the response of the climate system to the changes in land cover and land use. Over the past 250 years, human settlement has made extensive changes to the landscape, primarily in the form of transforming forests into pastures and croplands. Given current trends, it is expected by 2100 that most of the natural vegetation will disappear in Africa and parts of Asia and that there will continue to be a reintroduction of forests in Europe and North America. Such massive changes in land cover produce large regional changes in the surface albedo. These in turn lead to changes in the global radiative forcing comparable to the change due to increasing greenhouse gas concentrations. Several presentations on current research were made, and plans were agreed to for the design of the two types of numerical experiments.

WCRP Task Force on Seasonal Prediction (22-26 August 2005) ICTP

The World Climate Research Program (WCRP) Task Force on Seasonal Prediction held a workshop in Trieste, Italy at the International Centre for Theoretical Physics on 22-26 August 2005. The workshop focused on assessing the current state-of-the-art in seasonal prediction and how the seasonal prediction community can work with the THORPEX community to enhance the availability of near real-time seasonal prediction data from operational centers. The workshop also finalized plans for the first WCRP Seasonal Prediction workshop that is to be held in Barcelona on June 4-8, 2007.

Correcting Tropical Biases Meeting, (8-9 September 2005) COLA

An ad-hoc multi-institutional project has been established to attempt to reduce the tropical biases in simulations of the current climate by coupled ocean-atmosphere-land general circulation models (GCMs). These biases include those commonly found in the annual mean (in non-flux-corrected models) and annual cycle of sea surface temperature in the equatorial Pacific and Atlantic, and in the structure and period of the variability of El Niño and the Southern Oscillation (ENSO) in the tropical Pacific. One example of the tropical bias that is present in nearly all coupled climate models is the so-called double ITCZ syndrome in the Pacific.

The group met at COLA on 8-9 September 2005. The meeting included discussion of hypotheses concerning the physical mechanisms for the various biases, concentrating on the tropical Pacific. GCM experiments were designed to test these hypotheses, to be performed by the participating modeling groups.

Correcting Tropical Biases Meeting (23 June 2006) Breckenridge, CO

The follow-on meeting of the ad-hoc Correcting Tropical Biases project was convened at the end of the Community Climate System Model (CCSM) Workshop in Breckenridge, CO on 23 June 2006. Descriptions of the first and second workshops, and ongoing work can be found at http://www.iges.org/ctbp/. There is also information and links to datasets on the web page from the first Tropical Biases Workshop, which was held at GFDL in 2003. Results from ongoing work on correcting tropical biases will be presented at the 3rd WGNE Workshop on Systematic Errors in Climate and NWP Models, to be held in San Francisco, February 12-16, 2007.

GO-ESSP Workshop (19-21 June 2006) LLNL

The Global Organization for Earth System Science Portals (GO-ESSP; http://go-essp.gfdl.noaa.gov/) is a collaboration designed to develop a new generation of software infrastructure that will provide distributed access to observed and simulated data from the climate and weather communities. GO-ESSP will achieve this goal by developing individual software components and by building a federation of frameworks that can work together using agreed-upon standards. The GO-ESSP portal frameworks will provide efficient mechanisms for data discovery, access, and analysis of the data. GO-ESSP collaborations are intended to increase the availability of climate and weather (atmosphere, ocean, ice, land, and biosphere) data to a range of communities. The traditional consumers of climate and weather data have been within the scientific community. Increasingly climate information is desired by other communities, including impacts researchers and policy and decision makers. Over the last decade the tremendous growth in the volume of climate and weather data has also contributed to an increase in demand.

GO-ESSP held its fifth community workshop on 19-21 June 2006 at the Lawrence-Livermore National Laboratory in Livermore, CA. A plenary session of the meeting was devoted to constructing an action plan for the community over the next one to three years. It was agreed that the thrust of the activities in this period should revolve around providing improved access to data for the proposed AR5 activity of the IPCC and that GO-ESSP would be re-established around specific activities. For each core activity, GO-ESSP will establish relevance to AR5; set targets (specific, measurable, achievable, and ideally on one- and three-year time scales); address what, if any, funding is available to achieve these goals, and suggest mechanisms for international collaboration; and identify who would do what. It was agreed that funding opportunities are likely to be limited to national initiatives, but it would be helpful to establish some specific documentation of the international scope which would be referable in national applications.

7.3.4 Scientific and Technical Collaborations

Scientists at COLA actively participate in collaborative investigations and nationally and internationally coordinated research, in order to take advantage of knowledge and talents possessed by other scientists and in order to more effectively make COLA scientific and technical contributions useful to the research community. Because of the focused nature of COLA basic and applied research and the relatively small size of the Center, a good balance between internally generated research ideas and cooperative activities with scientists at other institutions is essential. Such a balance promotes both COLA's continued productivity and the advance of our global understanding of the Earth's climate. COLA scientists have several natural collaborations with individuals at other research centers, and they participate in multi-institutional collaborations with the other major US climate modeling centers. The following are among the projects in which COLA scientists are engaged:

- *Community Climate System Model* – COLA scientists have adopted the CCSM as a seasonal prediction research tool and are creating a set of control hindcasts with initial states of the global atmosphere, world oceans and global land surface that are derived from the observed; these hindcasts will be shared with the CCSM community. COLA scientists are also participating in CCSM sub-model working groups; using CCSM and its sub-models in a multi-model context to evaluate model dependence of climate sensitivity and predictability; and participating in development of the Community Land Model. COLA hosted a workshop on correcting tropical biases that has led to a group of experiments designed to test various hypotheses about the origin of systematic errors in CCSM and other coupled models.

- *NOAA Applied Research Centers Consortium* – COLA scientists are working with other Applied Research Centers (ARCs) of NOAA to test the sensitivity of coupled ocean-atmosphere models to the specification of the ocean initial state, and COLA is helping to coordinate the coupled model prediction research of the ARCs.
- *NOAA Climate Test Bed* – Created in 2004, the NOAA Climate Test Bed (CTB) is intended to significantly increase the number and skill of NOAA's operational climate forecast products by accelerating the transfer of research and development into improved NOAA operations. The CTB serves as a conduit between the operational, academic and research communities. COLA scientists help guide the CTB at all levels, with representation on the Scientific Advisory Board and the Climate Science Team, they are actively engaged in the analysis of Climate Forecast System (CFS) hindcast data, and they are using the CFS in several ways to further refine that model's prediction capability and to understand its behavior and predictability. A recent grant (T. DelSole, principal investigator) from the NOAA Climate Program Office was awarded at the end of 2005 to support research on empirical correction schemes to be used with models in CTB.
- *NASA Modeling, Analysis and Prediction project* – COLA scientists are engaged in a collaborative project with scientists at NASA Goddard Global Modeling and Assimilation Office on ways to evaluate and improve the performance of the GEOS5 climate prediction system. A grant (J. Kinter, principal investigator) from NASA was awarded at the end of 2005 to support this collaboration.

COLA scientists are also leading or participating in several multi-institutional working groups and model comparison projects including:

<u>Climate of the 20th Century (C20C)</u>

- COLA and the Hadley Centre, U.K., are coordinating this project
- The International CLIVAR C20C project (Folland et al., 2002; *CLIVAR Exchanges*; http://www.clivar.org/publications/exchanges/ex24/ex24.pdf) is focused on simulating and understanding the climate variability during the past 130 years. This includes understanding the impact of changes in SST, sea ice, land surface conditions and atmospheric composition and the attribution of the major climate anomalies observed during that period. Several workshops have been jointly organized by COLA and Hadley Centre scientists. The project is currently running two series of experiments (1) employing a new strategy called the "pacemaker" protocol, and (2) including the change of land cover and land use over the 20th century.

<u>Global Land-Atmosphere System Study (GLASS)</u>

- COLA is a participating center in GLASS, including the Project to Intercompare Land-surface Parameterization Schemes (PILPS) and the Global Soil Wetness Project (GSWP), the latter of which COLA acts as lead center

- GSWP is an ongoing environmental modeling research activity of the Global Land-Atmosphere System Study (GLASS) and the International Satellite Land-Surface Climatology Project (ISLSCP), both contributing projects of the Global Energy and Water Cycle Experiment (GEWEX). Its goals are to (1) produce state-of-the-art global data sets of land surface fluxes, state variables, and related hydrologic quantities; (2) develop and test large-scale validation, calibration, and assimilation techniques over land; (3) provide a large-scale validation and quality check of the ISLSCP data sets; and (4) compare Land Surface Schemes (LSSs), and conduct sensitivity studies of specific parameterizations and forcings, which should aid future model and data set development.
- A series of papers appeared or were submitted in 2005 documenting the multi-model sensitivity of the climate to variations in the land surface

Asia-Pacific Climate Center (APCC)

- COLA, University of Hawaii and Seoul National University in Republic of Korea are coordinating this project
- The Asia-Pacific Economic Cooperation (APEC) has established a climate network for the exchange of regional climate information, particularly climate forecast information, among the APEC Member Economies, and to ultimately contribute to the social and economic benefits of member economies as well as the reduction of natural disasters caused by unusual climate and weather events. The APEC Climate Center (APCC) has been established in Busan, Korea to implement an institutionalized communication channel for more effective exchange of regional climate information among member economies. One of the first projects of the APCC is Climate Prediction and its Application to Society (CliPAS). COLA scientists attended the opening ceremonies for APCC, hosted the first CliPAS workshop, attended the second CliPAS workshop, and regularly provide both two-tier and one-tier real-time predictions to the multi-model ensemble produced by CliPAS.

7.3.5 Panels, Committees and Working Groups

The research scientists at COLA are called upon from time to time to serve as members of national and international review panels and program planning committees. The following table provides an alphabetical list of the panels and committees on which COLA scientists served during 2002-2006.

AGU, Lorenz Lecture Committee	**V. Krishnamurthy,** member
AGU, Executive Committee, Nonlinear Focus Group	**V. Krishnamurthy,** member
AMS Comm. on Hydrology	**P. Dirmeyer,** member
Climate Dynamics (peer-reviewed journal)	**E. Schneider,** executive editor
	B. Kirtman, associate editor
Climate Simulation Laboratory Allocation Panel	**J. Kinter,** chair
COPES Task Force for Seasonal Prediction	**B. Kirtman,** chair
Cyberinfrastructure in Atmos. Sci.	**J. Kinter,** chair
ECPC Review Panel (2005)	**J. Kinter,** chair
GrADS and GDS Developers Group	**B. Doty,** chair
ICTP Physics of Weather and Climate SAC	**J. Shukla,** member
IGBP ILEAPS SSC	**P. Dirmeyer,** member
Int'l. CLIVAR Regional Climate Modeling Group	**B. Kirtman,** member
Int'l. CLIVAR WG on Seasonal to Interannual Prediction	**B. Kirtman,** co-chair
Int'l. GEWEX GLASS Panel	**P. Dirmeyer,** chair
Int'l. GEWEX Global Soil Wetness Project	**P. Dirmeyer,** chair
Int'l. GEWEX ISLSCP SSC	**P. Dirmeyer,** member
Int'l. GEWEX Modeling and Prediction Panel	**P. Dirmeyer,** member
ISLSCP SSC	**P. Dirmeyer,** member
Journal of Climate (peer-reviewed journal)	**D. Straus,** editor
NAS/NRC Comm. to Review GAPP SIP	**P. Dirmeyer,** member
NASA ESMF Advisory Board	**P. Schopf,** chair
NCAR GSP External Advisory Panel	**T. DelSole,** member
NCAR Scientific Computing Division Advisory Panel	**J. Kinter,** member
NOAA Climate Change Data and Detection Panel	**J. Kinter,** member
NOAA Climate Test Bed SAB	**J. Kinter,** member
NOAA Climate Test Bed Climate Science Team	**B. Kirtman,** member
NSF Geosciences Advisory Comm.	**J. Kinter,** member
NSF Advisory Committee for Cyberinfrastructure	**J. Kinter,** member
NSF Geosciences ITR Review Panel	**T. DelSole,** member
NSF Physical Oceanography Panel	**B. Klinger,** member
Petascale Collaboratory for the Geosciences	**J. Kinter,** member
THORPEX Int'l. Science Coordination Comm.	**J. Shukla,** member
Tropical Biases Meeting Organizing Comm.	**E. Schneider,** chair
	J. Kinter, member
U.S. CLIVAR Austral-Asian Monsoon WG	**B. Kirtman,** member
US CLIVAR PPAI	**B. Kirtman,** member
U. S. CLIVAR SSG	**P. Schopf,** member
U.S. Global Water Cycle Program SSG	**P. Dirmeyer,** member
WCRP GEWEX/CEOP representative to COPES	**P. Houser,** representative
WCRP Joint Scientific Committee	**J. Shukla,** member
WCRP Modeling Panel	**J. Shukla,** chair
	B. Kirtman, member
WCRP Observations Panel	**J. Shukla,** member

Acronyms used in the above table:

AGU	American Geophysical Union
AMS	American Meteorological Society

CEOP	Coordinated Enhanced Observing Period (GEWEX program)
CLIVAR	Climate Variability and Predictability program
COPES	Coordinated Observation and Prediction of the Earth System
ELDAS	European Land Data Assimilation System
GAPP	GEWEX Americas Prediction Program
GDS	GrADS Data Server (distributed data management software developed at COLA)
GEWEX	Global Energy and Water Cycle Experiment
GLASS	Global Land-Atmosphere System Study
GrADS	Grid Analysis and Display System (open source software developed at COLA)
GSP	Geophysical Statistics Program
ICTP	Abdus Salam International Center for Theoretical Physics (Trieste, Italy)
IGBP	International Geosphere-Biosphere Programme
ILEAPS	Integrated Land Ecosystem-Atmosphere Process Study
ISLSCP	International Satellite Land Surface Climatology Project
ITR	Information Technology Research
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
PPAI	Prediction, Predictability and Applications Interface
SAB	Scientific Advisory Board
SAC	Scientific Advisory Committee
SIP	Science and Implementation Plan
SSC	Scientific Steering Committee
SSG	Scientific Steering Group
THORPEX	A Global Atmospheric Research Programme (named for Prof. Alan Thorpe)
WCRP	World Climate Research Programme
WG	Working Group

WEB PAGES

Continuing and expanded use of the World Wide Web for sharing and disseminating information continues to be an effective medium for distribution of COLA products and services.

IGES Home Page

The IGES home page (www.iges.org) remains a popular, attractive and easy to use resource for our colleagues and for the public. The IGES home page is the primary Internet source for information about COLA personnel, research and publications (including COLA Technical Reports), GrADS information and software (www.iges.org/grads/), and is the electronic distribution site for COLA's experimental El Niño forecasts. COLA uses the home page to disseminate the ELLFB (www.iges.org/ellfb/). The home page is linked to information about the joint Climate Dynamics Ph.D. program with George Mason University (www.scs.gmu.edu/climate/climate_phd.html).

Weather Forecasts and Climate Information

Among the most popular components of COLA web pages, a full range of forecaster quality maps and plots is provided of current weather and climate predictions, as well as weather conditions, atmospheric analyses and related products generated from data available from the National Centers for Environmental Prediction (NCEP) using the Grid Analysis and Display System (GrADS). This service (www.wxmaps.org) attracts a very large volume of traffic on the COLA home page, with an average of over 200 GB (billion bytes) delivered each month in response to nearly 5 million individual requests from nearly 200,000 unique requestors.

Experimental Long-Lead Forecast Bulletin

COLA continues to publish the Experimental Long Lead Forecast Bulletin (ELLFB). The purpose of the ELLFB is to provide an opportunity for operational centers and research groups to present experimental forecasts with long lead-time. Ultimately, this exchange of experimental forecast techniques is intended to stimulate climate-forecasting research.

The ELLFB is published on a quarterly basis and includes both dynamic and statistical real-time forecasts of tropical Atlantic and Pacific sea surface temperature anomalies at lead times of up to 18 months. There are also several forecasts issued for rainfall and surface temperature anomalies over most of North America and relatively small regions of South America and Africa. The ELLFB is made available to the public on the World Wide Web (www.iges.org/ellfb/) free of charge. The ELLFB is currently being edited by Ben Kirtman of COLA. While this service had at one time up to 700 subscribers who received the formerly circulated print edition, its popularity has waned with the advent of more timely and comprehensive experimental predictions from the International Research Institute for Climate and Society (IRI).

GrADS and the GrADS Data Server

The GrADS computer code became open source during this project period. Web pages providing support for downloads of the source and selected executables, documentation and a user help facility are provided from the COLA home page.

The GrADS Data Server (GDS – w w w.iges.org/grad/gds/) technology, originally developed in collaboration with George Mason University under a grant from NASA, has been made publicly accessible from COLA. In addition, the GDS has been used to serve a great many data sets that are of great value to collaborators as well as other weather and climate scientists, and the site has proven enormously popular. The GDS is being used to manage the vast holdings of observational and model output data at COLA, and a GDS installed at NCAR is also used to analyze supercomputer model output. For example, between 1,000 and 1,500 unique Internet addresses used the GDS at COLA and NCAR monthly in 2004, making over 2 million requests for data. This capability is extremely helpful to users of U.S. NWS data sets that are stored in GRIB format, which is unwieldy for those who don't wish to write special purpose programs to decode and use GRIB data.

Special Purpose Web Pages

Several special-purpose home pages are part of the suite of pages at COLA. For example, under funding from a NASA grant, a web page was developed for analyses and forecasts of the Indian monsoon (www.monsoondata.org). The COLA ftp site is frequently used to exchange data sets or information of interest to collaborators, notably the distribution of the lower boundary conditions data sets for the Climate of the 20th Century project (www.iges.org/c20c/), the multi-model results of the GSWP-2 project (www.iges.org/gswp/), the land surface memory project (www.iges.org/wcr/), and the cholera and climate project (for use by team members only).

7.4 Facilities

Offices

The Center maintains offices in suites 302 and 109 of the Centerpark Office Park, 4041 Powder Mill Road, Calverton, Maryland. The office suites occupy about 15,000 square feet, including public rooms for the reception area, seminar room, library and conference room. Two computer laboratories, a peripheral equipment room, a communications hub and storage space are also included. The majority of the space is private offices for science staff. Space is reserved for graduate students and visiting scientists. IGES also maintains offices in suite 500 of the same office building that houses the Center for Research on the Environment and Water.

Computing Facility

The intensive numerical climate modeling and analysis of large volumes of data which are required for COLA research projects place large demands on the computational, data communications and visualization capabilities COLA provides. The local computer and communications facility is meeting a portion of these demands using high-end commodity hardware and a variety of application software (commercial, open-source and COLA-developed) for interactive data analysis and visualization. The COLA computing facility, as of the end of 2006, has 850 GFLOPS supercomputing capacity, and the total disk capacity is currently 73 TB. Important additions to the facility in 2006 were an upgrade to the supercomputer cluster, establishing connectivity to Internet 2, expansion and improvement of the local networking infrastructure, and a new centrally managed backup facility for key datasets. The computing facility consists of compute nodes, storage and analysis nodes, communications, web services and desktops.

Compute nodes: The computationally intensive component of the COLA computing facility includes 176 AMD processors in the XC 4000 cluster, 40 Alpha processors in symmetric multi-processor (SMP) nodes with a mixture of 2- and 4-processor configurations, and 20 Intel and AMD processors in SMP (2-processor) nodes.

Storage and analysis nodes: The data produced both on the COLA compute nodes and at remote supercomputing facilities are subsetted, transferred and stored at COLA using 38 processors (Alpha, PowerPC, and Intel) running Unix, Linux and OS X, which support a total of 73 TB disk capacity. Six of these systems are configured with automatic tape library systems for archival of data sets, and there is an additional dedicated tape server with a 10 TB capacity for key mission critical data sets.

Communications: The compute nodes and storage and analysis nodes are connected via a switched Gigabit network (1,000 Mb/s), which was upgraded to new equipment in 2006. These systems and the desktop systems are connected via a local switched network that is is a mixture of fast and gigabit ethernet (100/1000 Mb/s). External connectivity is provided by a gigabit ethernet connection to Internet 2, and by three additional T1 circuits (1.5 Mb/s each) to multiple Internet service providers.

Web services: A dual-processor system hosts the COLA home page and related content. Two other dual-processor systems provide data services to the community via the GrADS Data Server (GDS) as well as providing access to real-time weather maps that are updated continuously using data retrieved from NOAA NWS. The latter two systems have 2 TB disk space dedicated to data services. For security reasons, the web systems are isolated from most of the internal network services at COLA.

8. PUBLICATIONS

8.1 Refereed Publications

The lists that follow are references for papers that have appeared, are in press or are in review for peer-reviewed publications. All the work documented in these papers has been fully or partly supported by research grants to COLA, which have been acknowledged. The lists are shown by year in chronological order. COLA authors are shown in bold.

2002 (19 refereed papers; 1 Ph.D. dissertation)

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Bailey, D. A., P. B. Rhines, and S. Häkkinen, 2005: Formation and pathways of North Atlantic Deep Water in a coupled ice-ocean model of the Arctic-North Atlantic Oceans. *Climate Dyn.*, **25**, doi:10.1007/s00382-005-0050-3.

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As this report goes to press in January 2007, not all 2006 submitted papers have reached their final disposition. The following list includes "Appeared" (papers published in the peer-reviewed literature), "In Press" (accepted for publication or in transition from manuscript to published article), and "In Review" (publication decision has not as yet been made). A total of 63 papers either appeared or were in press and 3 dissertations were accepted in 2006, a new high point for COLA peer-reviewed publications.

Appeared (28 refereed papers; 3 dissertations):

Bates, S., 2006: The Role of the Annual Cycle in the Coupled Ocean-Atmosphere Variability in the Tropical Atlantic Ocean. *Ph.D. Diss.*, George Mason University.

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<u>In Press (35 refereed papers)</u>:

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<u>In Review</u> (32 manuscripts; includes *submitted* and *in revision*)

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DeWitt, D. G., **D. M. Straus**, and **E. K. Schneider**, 2006: Dynamics of mid-latitude ENSO response in GCM experiments: Direct and indirect effects of parameterization changes. *J. Climate* (in review).

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Drbohlav, H.-K., and B. Wang, 2006: Mechanism of the northward propagating intraseasonal oscillation in the south Asian monsoon region: results from an atmospheric intermediate model. *J. Climate* (in review).

Gao X., **P.A. Dirmeyer, Z. Guo, M. Zhao**, B. Decharme, G. Niu, and S. Mahanama, 2006: An approach for remote sensing validation of land surface schemes on a global scale. *J Hydrometeor.* (in review).

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Hu, Z.-Z., B. Huang, and **Kathy Pegion**, 2006: Leading patterns of the tropical Atlantic variability in a coupled GCM. *Geophy. Res. Lett.* (in review).

Hu, Z.-Z. and **B. Huang**, 2006d: Physical processes associated with tropical Atlantic SST gradient: Part II: The anomalous evolution in the southeastern ocean. *J. Climate* (in review).

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Kallummal, R., and **B. P. Kirtman**, 2006: Validity of the linear stochastic view of ENSO in a CGM. *J. Atmos. Sci.* (in review).

Kirtman, B. P., D. Min, P. S. Schopf and **E. K. Schneider,** 2006: A new approach for coupled GCM sensitivity studies. *Clim. Dyn.,* (in review).

Kirtman, B. P., **R. Wu**, and S. Y. Yeh, 2006: Internal ocean dynamics and climate variability. *J. Atmos. Sci.* (in review)

Krishnamurthy, V., and **J. Shukla**, 2006: Seasonal persistence and propagation of intraseasonal patterns over the Indian monsoon region. *Clim. Dyn.* (in review).

Liang, J., S. Yang, **Z.-Z. Hu**, **B. Huang**, A. Kumar, and Z. Zhang, 2006: Predictable Patterns of the Asian and Indo-Pacific Summer Precipitation in NCEP CFS. *Climate Dyn.* (in review).

Manganello, J. V., 2006: The influence of sea surface temperature anomalies on low-frequency variability of the North Atlantic Oscillation. *Climate Dyn*. (in review).

Manganello, J. V., and **Huang, B**., 2006: The influence of the mean state on the annual cycle and ENSO variability: a sensitivity experiment of a coupled GCM. *J. Climate* (in review).

Misra, V. and **L. Marx**, 2006: Role of the inversion clouds in a coupled model simulation over the equatorial Pacific Ocean. Part I: Sensitivity of the mean climate. *Mon. Wea. Rev.* (in review).

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Misra, V., **L. Marx**, **J. L. Kinter III**, **B. P. Kirtman**, **Z. Guo**, **D. Min**, **M. J. Fennessy**, **P. A. Dirmeyer**, **R. Kallumal** and **D. M. Straus**: Validating and understanding ENSO in two coupled climate Models. *Tellus* (in review).

Peters-Lidard, C. D., P. R. Houser, Y. Tian, S. V. Kumar, J. Geiger, S. Olden, L. Lighty, **B. Doty**, **P. A. Dirmeyer**, **J. Adams**, K. Mitchell, E.F. Wood, J. Sheffield, 2006: High performance earth system modeling with NASA/GSFC's Land Information System. *Innov. Sys. Software Eng*., (in review).

Rodo, X., **B. A. Cash**, J. Ballester, F. Justino, and M. A. Rodriguez-Arias, 2006: Atmosphere/ocean interactions linking the tropical Pacific and Mediterranean region: Idealized scenarios for the Mediterranean basin from a warmed tropical north Atlantic Ocean. *Global Planetary Change* (in review).

Schneider, E. K., 2006: Stochastic forcing of surface climate. *J. Atmos. Sci.* (in review).

Vikhliaev, Y., B. Kirtman, and **P. Schopf**, 2006: Extra-tropical north Pacific bred vectors. *J. Climate* (in review).

Wu, R. and **B. P. Kirtman**, 2006c: Roles of the Indian Ocean in the Australian summer monsoon-ENSO relationship. *J. Climate* (in review).

Wu, R., and **B. P. Kirtman**, 2006c: Regimes of local air-sea interactions and implications for performance of forced simulations. *Climate Dynamics* (in review).

Wu, Z., and N. E Huang, 2006: Ensemble Empirical Mode Decomposition: a noise-assisted data analysis method. *Proc. R. Soc. Lond. A* (in review).

8.2 Technical Reports

The COLA Technical Reports (CTR) series provides a completely up-to-date view of current COLA research. The reports are internally reviewed, posted on the web, mailed in hardcopy to a list of subscribers and, usually, submitted to peer-reviewed journals as soon as the work is completed. This enables faster communication of research results that can sometimes languish in the publication process for up to two years. The list below of 115 CTRs appearing in 2002-2006 is arranged in alphabetical order by first author.

Altshuler, E., M. J. Fennessy, J. Shukla, H. Juang, E. Rogers, K. Mitchell, and M. Kanamitsu, 2002: Seasonal simulations over North America with a GCM and three regional models. *COLA Tech. Rep.*, **115**, 60 pp. (March).

Bhatt, U. S. and B. P. Kirtman, Z.-Z. Hu, E. K. Schneider, 2002: Potential for influence of land surface processes on ENSO. *COLA Tech. Rep.*, **126**, 32 pp. (October).

Bhatt, U. S., E. K. Schneider and D. DeWitt, 2002: Influence of North American land processes on north Atlantic SST variability. *COLA Tech. Rep.*, **112**, 50 pp. (February).

DelSole, Timothy, 2006: A Bayesian Framework for Multimodel Regression. *COLA Tech. Rep.*, **228**, 46 pp. (October)

DelSole, Timothy, 2006: Low-Frequency Variations of Surface Temperature in Observations and Simulations. *COLA Tech. Rep.*, **202**, 45 pp (January).

DelSole, Timothy, 2006: Optimal Perturbations in Quasigeostrophic Turbulence. *COLA Tech. Rep.*, **205**, 47 pp (January).

DelSole, Tim, 2003: Predictability and Information Theory. Part I: Measures of Predictability, *COLA Tech. Rep.*, **146**, 43 pp (May).

DelSole, Timothy, 2003: Predictability and Information Theory. Part II: Imperfect Forecasts, *COLA Tech. Rep.*, **148**, 46pp. (June).

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DelSole, T. and J. Shukla, 2002: Linear Prediction of Indian Monsoon Rainfall. *COLA Tech. Rep.*, **114**, 58 pp. (March).

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DelSole, T. and P. Chang, 2002: Predictable component analysis, canonical correlation analysis, and linear inverse models. *COLA Tech. Rep.*, **117**, 27 pp. (June).

DelSole, Timothy and J. Shukla, 2005: Specification of Wintertime North American Surface Temperature. *COLA Tech. Rep.*, **179**, 59 pp. (March).

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Dirmeyer, Paul A., 2004: The land surface contribution to boreal summer season predictability. **172,** 34 pp. (September)

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Dirmeyer, Paul and Kaye Brubaker, 2005: Global Characterization Of The Hydrologic Cycle From A Quasi-Isentropic Back-Trajectory Analysis Of Atmospheric Water Vapor. *COLA Tech. Rep.*, **196**, 33 pp (October).

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Dirmeyer, Paul A., Xiang Gao, Mei Zhao, Zhichang Guo, Taikan Oki, and Naota Hanasaki, 2005: The Second Global Soil Wetness Project (GSWP-2): Multi-Model Analysis and Implications for our Perception of the Land Surface. *COLA Tech. Rep.*, **185**, 44 pp. (May).

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Gao, Xiang, Paul A. Dirmeyer, Zhichang Guo, Mei Zhao, Bertrand Decharme, Guoyue Niu and Sarith Mahanama, 2004: An approach for remote sensing validation of land surface schemes on a global scale. **173,** 42 pp. (October)

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Guo, Zhichang Paul A. Dirmeyer, Zeng-Zhen Hu, Xiang Gao, and Mei Zhao, 2006: Evaluation of GSWP-2 Soil Moisture Simulations, Part 2: Sensitivity to External Meteorological Forcing. *COLA Tech. Rep*., **215**, 35 pp. (May).

Hu, Zeng-Zhen and Bohua Huang, 2005a: On the Significance of the Relationship between the North Atlantic Oscillation in Winter and Atlantic SST Anomalies. *COLA Tech. Rep*., **178**, 34 pp. (February).

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Kirtman, B. P., 2002: The COLA anomaly coupled model: ensemble ENSO prediction. *COLA Tech. Rep.*, **125**, 52 pp. (September).

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Klinger, Barry A., Bohua Huang, Ben P. Kirtman, Paul Schopf, and Jiande Wang, 2004: Monthly Climatology of Friction Velocity Cubed from SSM/I Wind Data. **169,** 16 pp. (July).

Krishnamurthy, V. and J. Shukla, 2005: Intraseasonal and Seasonally Persisting Patterns of Indian Monsoon Rainfall. *COLA Tech. Rep.*, **188**, 41 pp. (June).

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Manganello, Julia V. and Bohua Huang, 2006: The Influence of the Mean State on the Annual Cycle and ENSO Variability: A Sensitivity Experiment of a Coupled GCM. *COLA Tech. Rep.*, **218**, 60 pp. (June).

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Misra, V., 2002: Tracing the mean climate simulation over the tropical Pacific in an AGCM. *COLA Tech. Rep.*, **124**, 38 pp. (September).

Misra, Vasubandhu, 2003: An Evaluation of the Predictability of Austral Summer Season Precipitation over South America, *COLA Tech. Rep.*, **137**, 35 pp. (March).

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Misra, Vasubandhu, 2004: A Diagnosis of Skill in an AGCM over Northeast Brazil. **171,** 23 pp. (September)

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Misra, Vasubandhu and Masao Kanamitsu, 2003: Anomaly Nesting: A Methodology to Downscale Seasonal Climate Simulations from the AGCM, *COLA Tech. Rep.*, **144,** 25 pp. (April).

Misra, Vasubandhu, and Larry Marx, 2006: Role of the Inversion Clouds in a Coupled Model Simulation over the Equatorial Pacific Ocean. Part II: Sensitivity of ENSO Variability. *COLA Tech. Rep.*, **219**, 30 pp. (July).

Misra, Vasubandhu, and Larry Marx, 2006: Role of the Inversion Clouds in a Coupled Model Simulation over the Equatorial Pacific Ocean. Part I: Sensitivity of the Mean Climate. *COLA Tech. Rep.*, **211**, 27 pp. (April).

Misra, Vasubandhu, Larry Marx, James L. Kinter III, Ben P. Kirtman, Zhichang Guo, Dughong Min, Mike Fennessy, Paul A. Dirmeyer, Rameshan Kallummal, and David M. Straus, 2006: Validating ENSO Simulation in Coupled Climate Models. *COLA Tech. Rep.*, **210**, 50 pp. (April).

Misra, Vasubandhu and Yuning Zhang, 2006: The Fidelity of NCEP-CFS Seasonal Hindcasts over Nordeste. *COLA Tech. Rep.*, **204**, 20 pp. (January).

Misra, V., 2002: The influence of Pacific SST on the precipitation over southern Africa diagnosed from an AGCM. *COLA Tech. Rep*., **119**, 22 pp. (June).

Misra, V., 2002: The teleconnection between the western Indian and the western Pacific Oceans. *COLA Tech. Rep.,* **131**, 24 pp. (November).

Miyakoda, K., J.L. Kinter III and S. Yang, 2002: The role of ENSO in the south Asian monsoon and pre-monsoon signals over the Tibetan plateau. *COLA Tech. Rep*., **113**, 44 pp. (February).

Schlosser, C. Adam and Ben P. Kirtman, 2003: Predictable Skill and its Attribution to Sea-Surface Temperature Variations in an Ensemble Climate Simulation, *COLA Tech. Rep*., **145**, 33 pp. (April).

Schneider, Edwin K., 2006: Evaluation of Noise Forcing of Low Frequency Surface Climate Variability. *COLA Tech. Rep*., **224**, 34 pp. (October).

Schneider, E. K., L. Bengtsson and Z.-Z. Hu, 2002: Forcing of Northern Hemisphere climate trends. *COLA Tech. Rep*., **116**, 37 pp. (June).

Schneider, Edwin K., Meizhu Fan, Ben P. Kirtman and Paul A. Dirmeyer, 2006: Potential Effects of Amazon Deforestation on Tropical Climate. *COLA Tech. Rep*., **226**, 41 pp. (October).

Schopf, Paul A., 2004: A Simple Mechanism for ENSO Residuals and Asymmetry. **170,** 35pp. (August).

Sikka, D. R., 2006: A Study on the Monsoon Low Pressure Systems over the Indian Region and their Relationship with Drought and Excess Monsoon Seasonal Rainfall. *COLA Tech. Rep*., **217**, 143 pp. (May).

Straus, David M., Susanna Corti, and Franco Molteni, 2005: Estimating Circulation Regime Properties: Uncertainty and Predictability. *COLA Tech. Rep*., **191**, 45 pp. (August).

Straus, David M. and V. Krishnamurthy, 2006: The Preferred Structure of the Interannual Indian Monsoon Variability. *COLA Tech. Rep*., **222**, 26 pp. (September).

Straus, David M. and Franco Molteni, 2003: Flow Regimes, SST Forcing, and Climate Noise: Results from Large GCM Ensembles, *COLA Tech. Rep*., **134**, 49 pp. (January).

Straus, David M., Dan Paolino, J. Shukla, Siegfried Shubert, Max J. Suarez, Arun Kumar, and Phil Pegion, 2002: predictability of the seasonal mean atmospheric circulation during autumn, winter, and spring. *COLA Tech. Rep*., **123**, 51 pp. (September).

Straus, David M. and J. Shukla, 2005: The Known, the Unknown and the Unknowable in the Predictability of Weather. *COLA Tech. Rep*., **175**, 20 pp. (January).

Vikhliaev, Yury, Ben Kirtman and Paul Schopf, 2006: North Pacific Bred Vectors in a Coupled GCM. *COLA Tech. Rep*., **221**, 47 pp. (August).

Vikhliaev, Yury, Paul Schopf, Timothy DelSole and Ben P. Kirtman, 2006: Finding Multiple Basin Modes in a Linear Ocean Model. *COLA Tech. Rep*., **209**, 38 pp. (March).

Wu, Qigang and David M. Straus, 2002: Co-existence of the annular/NAO and cold ocean-warm land regimes in Northern Hemisphere wintertime variability. *COLA Tech. Rep*., **132**, 2002, 33 pp. (December).

Wu, Qigang and David M. Straus, 2003: AO, COWL and Observed Climate Trends, *COLA Tech. Rep*., **143**, 44 pp. (April).

Wu, Qigang and David M. Straus, 2003: Multiple Planetary Flow Regimes and the Eddy Forcing in Northern Hemisphere Wintertime Variability, *COLA Tech. Rep*., **142**, 16 pp. (April).

Wu, Renguang Zeng-Zhen Hu, and Ben P. Kirtman, 2003: Evolution of ENSO-related Rainfall Anomalies in East Asia, *COLA Tech. Rep*., **138**, 41 pp. (March).

Wu, Renguang, James L. Kinter III, and Ben P. Kirtman, 2003: Discrepancy of Interdecadal Changes in the Asian Region between the NCEP-NCAR Reanalysis and Observations, *COLA Tech. Rep*., **157**, 35 pp. (November).

Wu, Renguang and B. P. Kirtman, 2002: On the impacts of the Indian summer monsoon on ENSO in a coupled GCM. *COLA Tech. Rep*., **129**, 42 pp. (November).

Wu, Renguang and Ben P. Kirtman, 2003a: Biennial Oscillation of the Monsoon-ENSO System in an Interactive Ensemble Coupled GCM, *COLA Tech. Rep*., **149**, 49 pp. (August).

Wu, Renguang and Ben P. Kirtman, 2003b: Impacts of the Indian Ocean on the Indian Summer Monsoon-ENSO Relationship, *COLA Tech. Rep*., **155**, 44 pp. (October).

Wu, Renguang and Ben P. Kirtman, 2003c: Understanding the Impacts of the Indian Ocean on ENSO Variability in a Coupled GCM, *COLA Tech. Rep*., **151**, 35 pp. (September).
Wu, Renguang and Ben P. Kirtman, 2004a: Roles of Indian and Pacific Ocean Air-Sea Coupling in Tropical Atmospheric Variability. **166,** 39 pp. (May).
Wu, Renguang and Ben P. Kirtman, 2004b: On the Relationship between Externally Forced Signal and Internally Generated Noise in Rainfall. **167**, 36 pp. (June).
Wu, Renguang and Ben P. Kirtman, 2004c: Near-annual SST Variability in the Equatorial Pacific in a Coupled General Circulation Model. **174,** 40 pp. (November).
Wu, Renguang and Ben P. Kirtman, 2005a: Changes in Spread and Predictability Associated with ENSO in an Ensemble Coupled GCM. *COLA Tech. Rep*., **184**, 41 pp. (May).
Wu, Renguang and Ben P. Kirtman, 2005b: Role of the Indian Ocean in the Biennial Transition of the Indian Summer Monsoon. *COLA Tech. Rep*., **200**, 34 pp. (November).
Wu, Renguang and Ben P. Kirtman, 2005c: Relationship of Spring and Summer East Asian Rainfall with Winter and Spring Eurasian Snow. *COLA Tech. Rep*., **201**, 45 pp. (December).
Wu, Renguang and Ben P. Kirtman, 2006: Regimes of Local Air-Sea Interactions and Implications for Performance of Forced Simulations. *COLA Tech. Rep*., **213**, 50 pp. (May).
Wu, Renguang and Ben P. Kirtman, 2006: Two Types of Dry Indian Summer Monsoons. *COLA Tech. Rep*., **220**, 23 pp. (July).
Wu, Renguang, Ben P. Kirtman, and Kathy Pegion, 2005: Local Air-Sea Relationship in Observations and Model Simulations. *COLA Tech. Rep*., **182**, 27 pp. (May).
Wu, Zhaohua and Norden E. Huang, 2003: A Study of the Characteristics of White Noise Using the Empirical Mode Decomposition Method, *COLA Tech. Rep*., **133**, 27 pp. (January).
Wu, Zhaohua and Norden Huang, 2005: Ensemble Empirical Mode Decomposition: A Noise Assisted Data Analysis Method. *COLA Tech. Rep*., **193**, 49 pp. (August).
Wu, Z. and D. W. Moore, 2002: The completeness of eigenfunctions of the tidal equation on an equatorial beta plane. *COLA Tech. Rep*., **118**, 18 pp. (July).
Wu, Z., E. K. Schneider and B. P. Kirtman, 2004: Causes of low frequency North Atlantic SST variability in a coupled GCM, **160**, 12 pp. (January).
Yeh, Sang-Wook, Jong-Ghap Jhun, In-Sik Kang and Ben P. Kirtman, 2003: The Decadal ENSO Variability in a Hybrid Coupled Model, *COLA Tech. Rep*., **136**, 37 99. (January).
Yeh, S.-W. and B. P. Kirtman, 2002a: On the relationship between the interannual and decadal SST variability in the north Pacific and tropical Pacific Ocean. *COLA Tech. Rep*., **121**, 27pp. (August).
Yeh, S.-W. and B. P. Kirtman, 2002b: The characteristics of signal versus noise SST variability in the North Pacific and the tropical Pacific Ocean. *COLA Tech. Rep*., **128**, 22 pp. (November).
Yeh, Sang-Wook and Ben Kirtman, 2004a: Global climate anomalies and decadal North Pacific SST variability in a coupled GCM. **162**, 31 pp. (March).
Yeh, Sang-Wook and Ben P. Kirtman, 2004b: Tropical Pacific Decadal Variability and ENSO amplitude modulation in a CGCM. **164**, 44 pp. (May).
Yeh, Sang-Wook and Ben P. Kirtman, 2004c: Pacific Decadal Variability and ENSO Amplitude Modulation. **168,** 15 pp. (June).
Yeh, Sang-Wook and Ben P. Kirtman, 2005a: The Origin of Decadal ENSO-Like Variability in a Coupled GCM. *COLA Tech. Rep*., **181**, 37 pp. (March).
Yeh, Sang-Wook and Ben P. Kirtman, 2005b: Dipole-like SST Variability in the Tropical Pacific. *COLA Tech. Rep*., **183**, 36 pp. (May).
Yeh, Sang-Wook and Ben P. Kirtman, 2005c: ENSO Amplitude Changes In Climate Change Projections. *COLA Tech. Rep*., **190**, 31 pp. (July).
Yeh, Sang-Wook and Ben P. Kirtman, 2003a: The Impact of Internal Atmospheric Variability on the North pacific Decadal SST Variability, *COLA Tech. Rep*., **140**, 22 pp. (March).
Yeh, Sang-Wook and Ben P. Kirtman, 2003b: The low-frequency variability of the tropical-North Pacific sea surface temperature teleconnections, *COLA Tech. Rep*., **156**, 40 pp. (November).

Zhao, Mei and Paul A. Dirmeyer, 2003: Pattern and Trend Analysis of Temperature in a Set of Seasonal Ensemble Simulations, *COLA Tech. Rep*., **150**, 22 pp. (September).

Zhao, Mei and Paul A. Dirmeyer, 2003: Production and Analysis of GSWP-2 Near-Surface Meteorology Data Sets, *COLA Tech. Rep*., **159,** 38 pp. (December).

Zhao, Mei, Paul Dirmeyer and Adam Schlosser, 2005: The Effects Of Downward Fluxes And Initial Conditions On The Skill Of Climate Predictions. *COLA Tech. Rep*., **197**, 39 pp. (October).

8.3 Invited Talks

Altshuler, E., 2006: The COLA/NWS Desktop Weather Forecast System (DWS). *SENAMHI*, Dakar, Senegal (22-26 May 2006).

Altshuler, E., 2006: The COLA/NWS Desktop Weather Forecast System (DWS). *SNET*, San Salvador, El Salvador (24-28 July 2006).

DelSole, T., 2002: Optimally Persistent Patterns: An Approach to Predictability and Decadal Variability Theory. *Climate Diagnostics Center*, Boulder, CO (16 May 2002).

DelSole, T., 2002: A Closure Theory of Quasigeostrophic Turbulence. *National Center for Atmospheric Research*, Boulder, CO (15 May 2002).

DelSole, T., 2002: Optimally Persistent Patterns: An Approach to Predictability and Decadal Variability Theory. *University of Maryland*, College Park, MD (21 February 2002).

DelSole, T., 2003: A Closure Theory for Quasigeostrophic Turbulence. *NCAR Stochastic Modeling of Geophysical Flows Workshop*, Boulder, CO (12-14 March 2003).

DelSole, T., 2003: Predictability of Weather and Climate Based on Information Theory. *Sloan Workshop on the Known, Unknown, and Unknowable in Predictability*, Savannah, GA (17-19February 2003).

DelSole, T., 2004: An Information Theory Perspective of Ensemble Methods. *Workshop on Ensemble Methods: From Weather Forecasting to Climate Change*, Met Office, Exeter, United Kingdom (20 October 2004).

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APPENDIX: ACRONYMS AND ABBREVIATIONS

AGCM – Atmospheric GCM
ACGCM – Anomaly Coupled GCM
AO – Arctic Oscillation
C20C – Climate of the 20th Century
CAM – Community Atmosphere Model (AGCM in current version of CCSM)
CCM – Community Climate Model (AGCM in earlier version of CCSM)
CCSM – Community Climate System Model (NCAR CGCM)
CFS – Coupled Forecast System (NCEP CGCM)
CFSIE – CFS Interactive Ensemble
CGCM – Coupled GCM
CLIVAR – Climate Variability program (WCRP)
CLM – Community Land Model
CNTL – control (run)
CO_2 – carbon dioxide
COLA – Center for Ocean-Land-Atmosphere Studies
COWL – Cold Ocean, Warm Land patter
DEMETER - Development of a European Multimodel Ensemble System for Seasonal-to-Interannual Prediction
DJF – December, January and February
DSP – Dynamical Seasonal Prediction
ECHAM – Max Planck Institute AGCM
EEMD – Ensemble EMD
EMD – Empirical Mode Decomposition
ENSO – El Niño and the Southern Oscillation
EOF – Empirical Orthogonal Function
ERA40 – ECMWF Reanalysis for 40 years
GCM – General Circulation Model
GEWEX – Global Energy and Water Experiment
GFS – Global Forecast System (NCEP atmospheric GCM)
GLACE – Global Land-Atmosphere Coupling Experiment
GSWP – Global Soil Wetness Project
IC – Initial Conditions
IGES – Institute of Global Environment and Society
IMF – Intrinsic Mode Functions
IPCC – Intergovernmental Panel on Climate Change
IRI – International Research Institute for Climate and Society
ISLSCP – International Satellite Land Surface Climatology Project
ITCZ – Inter-Tropical Convergence Zone
JAS – July, August and September
JFM – January, February and March
JJAS – June, July, August and September
LIS – Land Information System

L-MEB - L-band Microwave Emission of the Biosphere
MAM – March, April and May
MAMJ – March, April, May and June
MOM – (GFDL) Modular Ocean Model (OGCM)
MSN – Maximum Signal-to-Noise
MSSA – Multi-channel Singular Spectral Analysis
NAM – Northern Hemisphere Annular Mode
NAO – North Atlantic Oscillation
NASA – National Aeronautics and Space Administration
NCAR – National Center for Atmospheric Research
NCEP – National Centers for Environmental Prediction
NOAA – National Oceanic and Atmospheric Administration
NSIPP – NASA Seasonal-to-Interannual Prediction Program
NTA – North Tropical Atlantic pattern
OGCM – Oceanic GCM
OLR – Outgoing Long-wave Radiation
PrCA – Predictable Component Analysis
ROC – Relative Operating Characteristics
SLP – Sea Level Pressure
SOI – Southern Oscillation Index
SSA – Southern Subtropical Atlantic pattern
WCRP – World Climate Research Program
SST – Sea Surface Temperature
STA – Sub-Tropical Atlantic pattern
WES – Wind Evaporation SST feedback

Center for Ocean-Land-Atmosphere Studies
Institute of Global Environment and Society
4041 Powder Mill Road, Suite 302, Calverton, MD 20705. USA
Telephone: 301 595 7000 Fax: 301 595 9793
www.iges.org