Statement to the US Commission on Ocean Policy

Climate Prediction Capabilities

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Recommendations

- Encourage enduring and comprehensive observational networks.
- Bridge gap between optimal design of observing networks and their ultimate value in forecast systems.
- Encourage national coordination of efforts and resource investments toward development and improvement of climate modeling and climate prediction tools.

Introduction

Climate prediction has advanced considerably in the past 20 years, but substantial room for improvement still exists (see review paper by Goddard et al. 2001[1] for more complete description of the current approaches to seasonal-to-interannual climate prediction and identification of prediction research frontiers). Such improvements rely critically on the establishment and maintenance of quality observing networks, particularly in the global oceans. Also crucial for improved climate prediction capability are increased computational and human resources and more coordinated management of current resources for model development.

The IRI (International Research Institute for Climate Prediction) is in the unique position within the research community and society at large in its ability to utilize different prediction tools and methodologies in order to produce the most reliable possible seasonal climate forecasts, and then to apply those forecasts to real world climate-sensitive problems including health, agriculture, energy and water resource management and disaster mitigation. This process, which is often referred to as 'end-to-end' climate forecasting, involves physical and social scientists at the IRI working closely with countries worldwide, particularly developing nations that are especially vulnerable to climate variability. Ultimately the relative value of climate forecasts on country-level economics and social welfare can be estimated. However, such goals are only achievable in the long-term, and these end-to-end projects are quite new. What can be estimated at this time is the quality of seasonal climate forecasts and where opportunities exist for improvements to climate forecasts, which will eventually impact the quality of decisions based on those forecasts.

State-of-the-art seasonal climate prediction

The current state-of-the-art in climate prediction employs a two-tiered dynamical prediction system (FIGURE 1); sea surface temperatures (SSTs) are predicted first, which then serve as the lower boundary forcing to atmospheric general circulation models (AGCMs). Although coupled ocean-atmosphere models (one-tiered system) hold promise for the future, their problems are still substantial, as will be discussed

[1] Goddard, L, S.J. Mason, S.E. Zebiak, C.F. Ropelewski, R. Basher, and M.A. Cane. 2001. Current approaches to seasonal-to-interannual climate predictions. *International Journal of Climatology*. **21**: 1111-1152. DOI: 10.1002/joc.636

later. The area over which skillful forecasting is possible can be increased by using several AGCMs. This is because different AGCMs use different parameterizations of sub-grid scale processes, leading to differing patterns and/or intensities of climate patterns. Such differences result in certain models being more skillful than others in certain places at certain times of the year for particular variables. By using a suite of AGCMs and a process called "multi-model ensembling" regional forecasts can rely most heavily on the model(s) that perform best over that region.

The climate system has inherent uncertainty, and climate forecasts must be interpreted/issued probabilistically. For each AGCM, an ensemble of forecast integrations is generated in order to reduce the chaotic component, or internal variability, of the atmosphere. The repeatable patterns in the ensemble are then that due to the surface (i.e. SST) forcing, which is the predictable part of the climate. To the extent that the SST-forced 'signal' is discernable above the internally driven 'noise', information can be provided about the likely tendency of the impending climate. However, in nature the signal and the noise are inseparable. Thus in the forecasts, the noise provides an envelope of potential outcomes around the most likely outcome. This distribution of possible outcomes underlies a probabilistic seasonal climate forecast, but as described covers only the uncertainty in the atmospheric component of the climate system. There is uncertainty in the oceanic component of the climate system also.

As SSTs drive the predictable part of the climate, it is imperative to use the best possible forecasts of SST anomalies, globally. Although the El Nino – Southern Oscillation (ENSO) phenomenon of the tropical Pacific is responsible for anomalous climate worldwide, changes in SSTs in the Indian and Atlantic Oceans can also have a substantial impacts on neighboring land areas, either on their own or by modifying ENSO teleconnections (FIGURE 2). For example, East Africa often experiences above-normal rainfall during El Nino events. At the same time, the Indian Ocean often becomes warmer than normal during El Nino events. Modeling studies have shown that it is actually the warm SST anomalies in the Indian Ocean that drive the increase in East Africa rainfall, and the warm tropical Pacific SST anomalies associated with El Nino would, on their own, force drier than normal conditions in that region. Such studies underscore the need for accurate forecasts of SSTs in all the tropical ocean basins. Currently different methods are used for predicting SSTs in each tropical ocean basin: dynamical predictions for the tropical Pacific and empirical models for the Indian and tropical Atlantic Oceans, based on the approach that yields the most skillful prediction.

Room for improvement in current state-of-the-art

Unfortunately the skill of AGCMs in reproducing seasonal climate has not increased much in the last 10 years. Model results are especially sensitive to differing parameterizations of convection and cloud processes, which have implications for both local thermodynamics related to local radiation and global thermodynamics related to the global hydrological cycle and the global heat budget. At this time most model development efforts are aimed at improving global heat balance, a primary concern of global change scientists. However, the effort of improving global heat balance often ignores issues that are of concern to seasonal prediction/variability scientists, and parameterizations that result from that focus often degrade the performance of the AGCMs for simulating surface climate variations, in particular temperature and precipitation.

At this time SST predictions for the tropical Pacific are the best. Skillful predictions for the tropical Pacific SSTs are due to our increased understanding of the ENSO phenomenon and our ability to model it as a result of the TAO/TRITON array of moored buoys in the equatorial Pacific region. That array of data available in real-time allows for the monitoring of ENSO, as well as initialization of ocean-atmosphere models that forecast ENSO. During the last 10 years, the largest gains in ENSO forecast skill has come from the assimilation of observed ocean data in initializing ocean models within the tropical Pacific. (FIGURE 3) Other observed data that are proving promising for further improving coupled model initialization, and thus ENSO prediction, are the NSCAT winds measured by a microwave radio scatterometer aboard the Advanced Earth Observing Satellite (ADEOS) and the sea-surface height data from the TOPEX/Poseidon orbiting satellite. Optimal use of the TOPEX/Poseidon data, however, depends on the availability of sub-surface salinity data in order to project the surface height anomaly onto the anomalous density profile that is a function of both temperature and salinity. The proposed system of ARGO floats holds great promise in this regard, both in terms of their global coverage and their retrieval of salinity profiles, which is currently a real weakness in initializing the sub-surface ocean.

The SST forecasts are not as good for the Indian and Atlantic Oceans as they are for the tropical Pacific largely because of the lack of observations, especially those available in real-time. For both the tropical Atlantic and Indian Oceans much debate still exists regarding the relative roles of thermodynamic forcing from atmospheric heat fluxes and dynamic forcing involving windstress and ocean circulation. Predictions for SSTs outside the Pacific are mostly from statistical models, and rely heavily on empirical relationships with ENSO. In some cases, such for the equatorial Atlantic, persistence of recently observed SST anomalies is the best possible forecast at present, unsurpassed by dynamical or statistical models. However, the errors associated with such a SST prediction leads to loss of predictability over the very climate-sensitive region of West Africa, predictability that does exist given perfect (i.e. observed) SSTs (FIGURE 4). Dynamical models do not perform well outside the Pacific, and this again comes from our limited understanding of the processes in those basins, and also from the lack of data that can be used to initialize the ocean structure in those basins.

Approximately 70% of the earth's surface is covered by ocean. As such, changes in the sea surface temperature patterns and associated convective activity, provide the dominant forcing for the overlying atmosphere. However, changes in the land surface, such as soil moisture, can also influence local climate considerably. Studies of floods and drought over the United States (e.g. 1993 and 1988, respectively) have shown that use of observed land surface conditions in AGCMs yield much improved distribution and intensity of anomalous rainfall in those years. Presently it is not possible to initialize the land surface for global climate predictions, because no such observing network is present. Some information on soil moisture over the United States is available, but the optimal use of this information in dynamical seasonal climate prediction is still under investigation.

Regarding the outputs of seasonal climate forecasts, there is increasing demand for information on the sub-seasonal, and even sub-monthly time scale. Particularly for agricultural applications of climate forecasts, information on the start of the rainy season, the character of the rainfall within a season (e.g. average intensity, extremes, dry spell duration), and frost potential could greatly benefit decision makers. Demand for forecasts with higher spatial resolution is also increasing. The potential for providing meaningful predictions of the seasonal characteristics of climate and at high spatial resolution is an area of active research. However, much of the research is spread thinly among many institutions with limited human and computing resources and limited communication between them. This activity is extremely labor and computer intensive, requiring the storage and subsequent analysis of unprecedented volumes of data. Additional resources for this area of research are clearly needed. On the other side of the problem, however, observational networks that provide data on similar space and time scales are also necessary. Such observations allow for verification of model simulations/predictions as well as the construction of statistically-based spatial or temporal downscaling models, that can be used for performance baselines.

The future of climate prediction

The future of seasonal-to-interannual climate prediction is coupled ocean-atmosphere models. In this "one-tier" prediction methodology, SST anomalies are generated by anomalies of the overlying atmospheric circulation instead of being imposed. This approach leads to better consistency between ocean and atmosphere variability. It also leads to probabilistic climate forecasts that directly account for uncertainties in SST evolution. Since the atmosphere has its own probability distribution associated with any particular SST pattern this amounts to a more complex situation of quantifying the joint distribution of uncertainty between the ocean and atmosphere. In a practical sense coupled ocean-atmosphere predictions will require a much larger set of ensembles to properly describe the probability distribution for a given season, and that will require substantially more computing resources.

As mentioned in the previous section improvements to the ocean observing network are essential to continuing improvements in SST prediction, necessary for climate prediction. Enhancements to overall coverage, spatial density, and types of data (e.g. sub-surface temperatures, salinities, and currents, and well as sea-surface heights and winds) lead directly to better understanding of the physical processes and thus better modeling and improved initialization of the ocean state for forecasting the evolution of the coupled ocean-atmosphere system.

Considerable research and development is still required for coupled models. Most coupled models have large systematic errors in reproducing the mean state and seasonal cycle as well as the interannual variability of the tropical oceans. Over the Pacific, coupled models either capture one or the other; those with a realistic seasonal mean state have a poor representation of ENSO variability, and vice versa. Over the Atlantic Ocean, almost all coupled ocean-atmosphere models produce a mean equatorial SST gradient opposite to that observed. Such errors in simulating the low frequency characteristics of the climate system are the main impediment to the use of one-tiered prediction systems for operational climate forecasting at this time.

Additional deficiencies in coupled models have also been identified, typically in the context of improving coupled models for SST prediction. To date, no model is able to simulate intra-seasonal variability such as the Madden-Julian Oscillation. Intra-seasonal variability is thought to be a part of the natural, internal variability of the atmosphere and is thus not strongly driven by changes in the underlying SSTs. Intra-seasonal variability is responsible for much of the variability associated with monsoon systems. It has also played a significant role in many El Nino events, in particular that of 1997-98, which owed much of its rapid development and unusual strength to several strategically timed MJO events. The ability to capture intra-seasonal variability in coupled models will be a big breakthrough, since such sub-seasonal variability is a primary source of uncertainty in forecasting ENSO. Just as specific weather is not predictable more than about a week in advance, however, neither will the precise evolution of these intra-seasonal events. Rather if the interannual variability in the strength and number of such events can be simulated, it will lead to the desired probability distributions in SST. Monitoring enabled by real-time observations has revealed the important role that intra-seasonal variability plays in the tropics, and ultimately the global climate, and has led to a much greater understanding of the physics of that variability.

The ability to reproduce the characteristics of the coupled climate system over all frequencies, from the mean state (and decade to century scale trends) to the intra-seasonal variability, should be the eventual goal of the modeling community. This is a large and difficult task. But, it will benefit the prediction community greatly, from the seasonal forecasts to the climate change scenarios. The problem requires the concerted coordinated efforts of national modeling centers together with considerable computing resources to develop and test models with the goal of capturing the full spectrum of temporal variability in mind.

Summary

- Encourage enduring and comprehensive observational networks.

Observational data is critical to every step of the seasonal climate prediction process. That data is used for physical understanding of SST and climate variability to better model it. It is used for verification of the resulting simulations/predictions. Most importantly, observed data, particularly in the oceans, allows for the initialization of the ocean state so that its future evolution can be better estimated.

As operational forecast centers develop methodologies to incorporate observations to initialize seasonal forecasts, it is essential that the data networks endure. Gaps in observational records may be a mere inconvenience to researchers, but they can be fatal to operational climate forecasts that rely on them. At the very least, unreliable data networks would certainly degrade forecast skill. Similarly coordinated observing systems that use a combination of platforms, such as in situ and satellite measurements are likely to provide the greatest benefit. In situ measurements will be necessary for sub-surface ocean data, which should be collected globally with good coverage if improvements to SST predictions in all tropical ocean basins are to be realized. Satellite measurements can provide high spatial and temporal coverage not possible by buoys or floats, in addition to providing information over land such as land use and potentially surface wetness or soil moisture.

- Bridge gap between optimal design of observing networks and their ultimate value in forecast systems.

Currently various observing networks and platforms are designed and deployed by different agencies and little coordination exists among them. Expense is often a major consideration when deciding what variables will be measured and with what spatial and temporal frequency. There may be scientific arguments for the minimum requirements of a particular data system, such as the spacing of the TAO/TRITON array be just dense enough to resolve equatorial waves. Similarly users of observed data want as much as is available, and often even more. To date, however, no coordinated effort exists to quantify the value of any observing network, such as in seasonal forecast systems. The exercise of trying to determine such value should help optimize the design of observing networks and, at the same time, yield more concrete justification for those networks. It is suggested that this process would be best incorporated explicitly into the planning, implementation, and resourcing of the observational systems themselves.

- Encourage national coordination of efforts and resource investments toward development and improvement of climate modeling and climate prediction tools.

The human effort and computational resources necessary to develop and test coupled ocean-atmosphere models is tremendous. In order to establish the usefulness of coupled models for seasonal-to-interannual climate prediction many realizations of many years must be run and analyzed. Since the observational data needed to initialize ocean models has only been available in the last 10-15 years, and mainly in the Pacific, researchers have to be very creative, if not always accurate, about how to estimate the ocean's state in the early years of the runs. Such work is time consuming and costly. Add in the demands of climate forecast users that want higher spatial and temporal resolution from seasonal forecasts, and the resource needs of the climate prediction community become very large very quickly. Coupled models and higher resolution climate forecasts are still areas of research, so the needs go beyond owning a computer capable of running such forecasts. With greater coordination among research centers, and a greater investment of human and computing resources towards these problems, progress will be made. Eventually, such forecasts may even merge into the same dynamical framework. At that time probabilistic seasonal forecasts will be more physically consistent, spatially and temporally informative, and, it would follow, more useful to society at large.

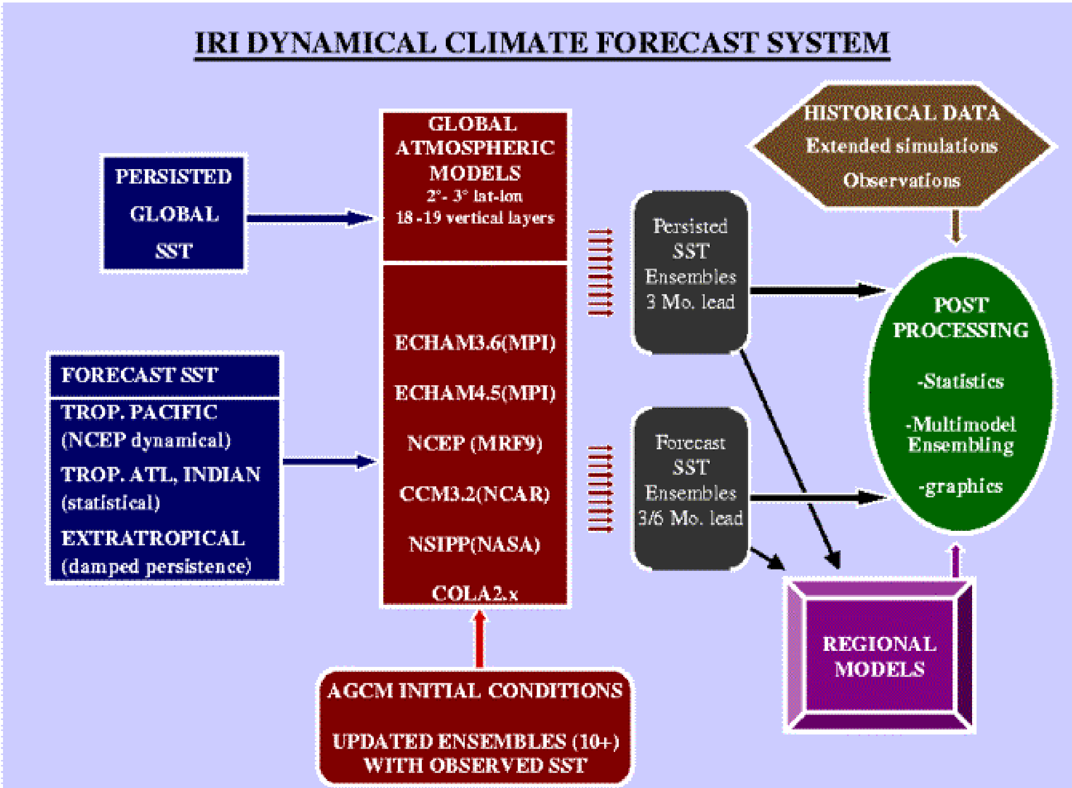

IRI DYNAMICAL CLIMATE FORECAST SYSTEM
PERSISTED GLOBAL SST
FORECAST SST
TROP. PACIFIC (NCEP dynamical)
TROP. ATL, INDIAN (statistical)
EXTRATROPICAL (damped persistence)
GLOBAL ATMOSPHERIC MODELS
2°- 3° lat-lon
18 -19 vertical layers
ECHAM3.6(MPI)
ECHAM4.5(MPI)
NCEP (MRF9)
CCM3.2(NCAR)
NSIPP(NASA)
COLA2.x
AGCM INITIAL CONDITIONS
UPDATED ENSEMBLES (10+) WITH OBSERVED SST
Persisted SST Ensembles 3 Mo. lead
Forecast SST Ensembles 3/6 Mo. lead
HISTORICAL DATA
Extended simulations
Observations
POST PROCESSING
-Statistics
-Multimodel Ensembling
-graphics
REGIONAL MODELS

FIGURE 1

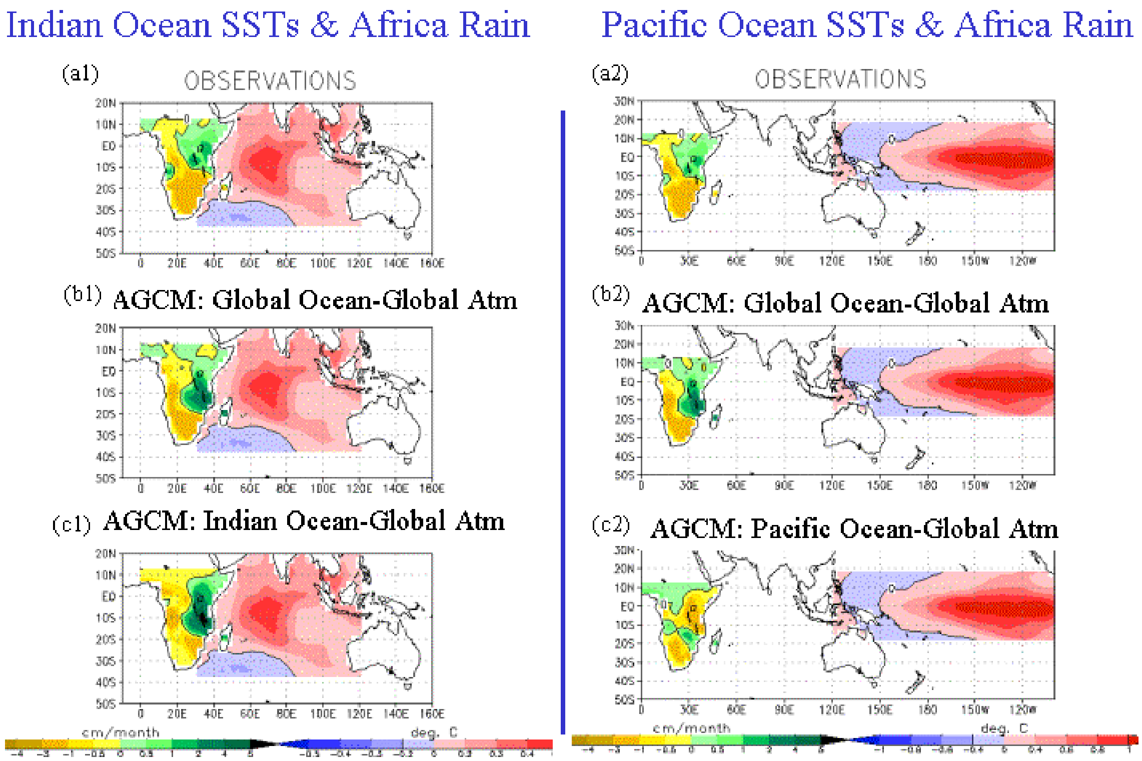


FIGURE 2: Importance of Indian Ocean for simulating eastern African rainfall. (a1) & (a2): Pattern of anomalous rainfall associated with SST anomalies in the Indian and Pacific Ocean, respectively, from observations. (b1) & (b2), similar to (a1) & (a2) except as simulated by an AGCM. (c1): rainfall pattern due to Indian Ocean only experiment. (c2) rainfall pattern due to Pacific Ocean only experiment. Goddard and Graham (1999)

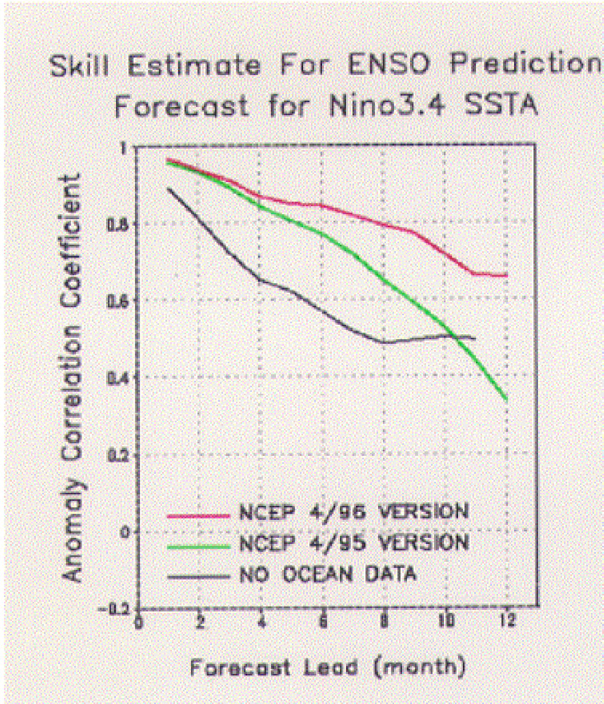
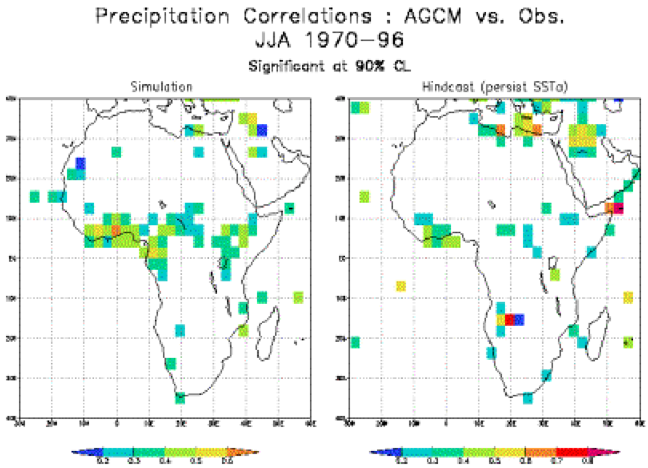


Figure 3: Impact of ocean initialization on NCEP coupled ocean-atmosphere model forecast system skill. Without ocean data assimilation (black line); with ocean data assimilation (green & red lines).



Loss of skill in AGCM due to imperfect predictions of SST

Dominant pattern of precipitation *error* associated with dominant pattern of SST prediction *error*

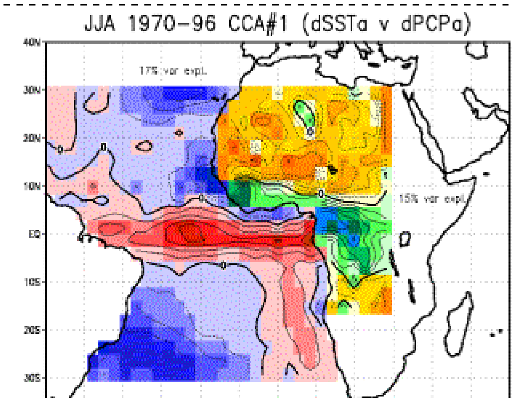


FIGURE 4