A POLICY FORUM: IMPROVING RESPONSES TO CLIMATE PREDICTIONS

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Panel 1

Progress Of Climate Science In Providing Information To Prepare And Respond To Seasonal Variations

POSITION PAPERS

Improving Responses to Climate Predictions: Climate Information in the 21st Century

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The development of reliable seasonal forecasts and successful responses to climate variations, including those of El Niño and La Niña, requires a full understanding of evolving climate conditions. This is made possible by a wide array of in situ and remote observing systems that provide measurements from the upper atmosphere to below the surface of the oceans. These measurements are often available in near real-time and provide indications of developing conditions that, in years past, were not realized until well after their onset. Significant advancements in observations and monitoring have been made during the last two decades, most notably in improved observing networks that now provide advanced warning of developing ENSO (El Niño/Southern Oscillation) episodes. The inability to detect significant climate events, such as the very strong 1982-83 El Niño episode, before they fully develop is now a relic of the past.

Improvements in observing systems have been complemented by significant advancements in the development of high quality long-term data sets. These historical records now provide the basis for understanding how evolving conditions compare to those of the past. The variations and changes in climate that have occurred over the previous decades and centuries provide an important source of information for understanding developing trends as well as the range of possibilities for what may occur in the future. Because the observations contained in these historical databases were often made with instruments and observing practices that differ from those of today, various techniques are needed for removing these artificial effects from the climate records. The design of homogeneity adjustment algorithms and techniques is the cornerstone of databases that allow current and evolving conditions to be placed in their proper historical perspective.

These observing systems and high quality historical records have more recently been applied to the continuous monitoring of climate conditions on the local, regional and global scales, with data and analyses distributed to decision-makers in many cases via the internet. Providing improved access to climate information is a primary focus within the National Oceanic and Atmospheric Administration (NOAA). For instance, at NOAA's National Climatic Data Center (NCDC), more than 4.5 terabytes of climate data were provided to customers in 2002, with approximately 90% of these data provided via the internet. This includes products and information developed specifically for climate assessment, including the monitoring of ENSO conditions and the associated effects.

Monitoring ENSO conditions

The evolution of the ENSO phenomena is identified through the observation of conditions in the equatorial Pacific and impacts in climate and weather conditions that occur in other regions of the world. Associated observations from the equatorial Pacific include measurements of surface and subsurface ocean temperatures, salinity, precipitation, outgoing longwave radiation, low level winds and atmospheric pressure.

The conditions most commonly associated with El Niño are warming sea surface temperatures in the equatorial Pacific from the coastal waters of Peru and Ecuador to the central Pacific, and conversely a cooling of these waters during La Niña. Current and historical sea surface temperature measurements throughout the equatorial Pacific are provided by NOAA's TAO/TRITON (Tropical Atmosphere Ocean/Triangle Trans Ocean Buoy Network) array of moored buoys, as well as other national and international moored and drifting buoys, NOAA's polar orbiting satellites and ocean-going ships. These sources have been combined into a single data set known as the Reynolds OI (Optimum Interpolated) data set of sea surface temperatures, which has a period of record from 1981 to the present (Reynolds et al., 2002).

Another data set, which was more recently developed at NCDC by Smith and Reynolds (2003), provides greater historical perspective by including sea surface temperatures from 1854 to the present. This data set relies on ship and buoy observations prior to 1981. NOAA's Comprehensive Ocean Atmosphere Data Set (COADS) is a third source of sea surface temperature observations with records that date to the mid-1800's (Woodruff et al., 1998) and is used in the Smith and Reynolds (2003) data set.

Wind speed and direction measurements from the surface to the upper troposphere are also used to monitor the development of warm and cold episodes. Upper air measurements of these conditions (for example at 850 and 200 millibars) are provided by radiosonde networks and are available as part of NCDC's Comprehensive Aerological Radiosonde Data Set (CARDS). CARDS provides data for more than 2300 upper air stations and contains over 27 million quality controlled radiosonde observations with records for many stations beginning as early as 1940 (Eskridge at al., 1995). Equatorial Pacific radiosonde observations are currently collected at locations such as the Marshall Islands and Cristobal in the Galapagos Islands.

Surface pressure observations are also an important part of ENSO monitoring. Historical sea level pressure station data are provided in NCDC's Global Historical Climatology Network and gridded sea level pressure data in NCDC's Extended Reconstructed SLP data set (Smith and Reynolds, 2002).

Convective precipitation is known to increase in the central and eastern equatorial Pacific during El Niño and decrease during La Niña events. Surface station precipitation measurements in this region are limited but are available at remote island locations. They are included in NCDC's Global Historical Climatology Network (GHCN), a data set of monthly precipitation totals that begins as early as 1697 and contains more than 20,000 stations from around the world (Peterson and Vose, 1998). It is updated during the first week of each month. The CAMS-OPI data set is another source of current and historic monthly precipitation data. It was developed at the Climate Prediction Center under the auspices of the Global Precipitation Climatology Project (GPCP) using a technique for merging rainguage observations with satellite-derived precipitation estimates and has greater spatial coverage than is provided by in situ measurements alone (Janowiak and Xie, 1999).

Monitoring the effects of ENSO throughout the world

Although the effects of ENSO on precipitation and temperature patterns in the equatorial Pacific are quite clear, the effects are not confined to this region. Through teleconnections, the warm and cold phases of ENSO are known to significantly influence many other regions of the world. Monitoring the global climate is made possible by some of the same systems and databases previously discussed as well as many others.

The US Climate Division Database and US Historical Climatology Network provide for the analysis of temperature and precipitation throughout the contiguous US. Data from the Automated Surface Observing System (ASOS) are also readily available for analysis of local conditions. NEXRAD radar data are sent from NWS sites across the US to NCDC and made available to the general public via the worldwide web on a daily basis. Satellite observations of data such as cloud cover, water vapor, surface wetness, temperature, precipitation and snow cover are also available for analysis and direct distribution to the general public via the internet.

These readily available data sources include, but are not limited to, NCDC's NEXRAD national mosaic reflectivity images (1995 to present), NEXRAD level II and III data, GOES browse server of satellite images (1992 to present), historical significant events satellite imagery, and global surface temperature, wetness, and snow cover anomalies from the Special Sensor Microwave Imager (1988 to present; Basist et al., 2000). Another dataset available from NCDC is the Integrated Surface Hourly (ISH) dataset, which comprises worldwide surface hourly and synoptic data from 1900 to present. The dataset is composed of several data sources merged into a common format, including input sources from NCDC and the US Navy and Air Force.

NCDC initiated a global climate monitoring program using these diverse sources of data in the late 1990's. By combining near real-time observations with past records, NCDC is able to place current conditions into accurate historical perspective and to assess evolving trends and extremes. These reviews are provided largely through the web-based publication of monthly State of the Climate reports, which are made available by the 15th of the following month.

These reports commonly include analyses of surface and upper air temperatures, which among other things, aid in understanding how temperatures on a global and regional basis vary during El Niño and La Niña episodes. The global average temperature is typically warmer during an El Niño episode, as evidenced by the record warm global temperatures that occurred during the very strong 1997-1998 El Niño episode. However, high quality instrumental records at NCDC show the record warm global temperatures to be part of an overall long-term warming trend of approximately 0.6° C per century since 1900 and a rate approximately three times higher since 1976.

Precipitation patterns, which are also affected by ENSO conditions in several parts of the world, are monitored from the global to the local level at NCDC. Record and near-record rainfall that occurred in Florida and other southern-tier states in the winter of 1997-1998 was followed by extremely dry conditions as La Niña quickly replaced El Niño in mid-1998. This contributed to devastating wildfires in Florida and developing drought conditions in the Southeast that did not end in many locations until late 2002.

Each State of the Climate report includes analyses of extreme events such as the Florida wildfires of 1998 and the western wildfires of 2000 and 2002 as well as heat waves and drought. These analyses are made possible not only by the data sets developed and maintained at NCDC but also by related research studies. Previous studies at NCDC determined which drought indices are most closely related to the incidence of wildfires. Another study provided a method for estimating the amount of precipitation needed to end drought as well as the climatological probability that the affected area would receive the necessary precipitation. More recent research efforts have studied the effects of climate and weather on major sectors of the US economy such as energy and agriculture and now provide measures of these impacts through various indices.

As evidenced by widespread drought that rapidly developed in 1998 and continues to affect parts of the US in 2003, ENSO can play a role in the incidence of drought in the US. The persistence and widespread nature of the drought that began in that year has contributed to an awareness by many decision-makers that operational drought monitoring programs can greatly assist in preparation and planning of response activities. NCDC uses numerous indicators of drought in assessing the severity and expanse of drought in the US as part of each State of the Climate report. These indicators are also used in preparing the US Drought Monitor, a weekly assessment of drought conditions in the US and Puerto Rico. This multi-organizational effort, which was initiated in 1999 by the National Weather Service, now forms the basis for a drought monitoring program for the continent of North America which began at NCDC in 2002.

NCDC also works with other federal and private sector scientists in providing a review of the previous year's climate and weather in a detailed annual climate assessment. This 50-page analysis of the previous year's climate and weather is published each June in the *Bulletin of the American Meteorological Society*. Other related climate monitoring activities include lead authorship of the past three World Meteorological Organization Annual Statements on the Status of the Global Climate.

Global sharing of climate data

Access to the worldwide in situ and satellite observations that are used in these, and other, climate monitoring activities is made possible through methods that rely on terrestrial and satellite transmission of data. For example, the TAO/TRITON buoy observations are transmitted to NOAA Polar-orbiting satellites, which relay the data to regional processing centers. These data are then made available to the meteorological community via the Global Telecommunications System (GTS).

The GTS consists of an integrated network, which interconnects meteorological telecommunication centers throughout the world. The circuits of the GTS are composed of a combination of terrestrial and satellite telecommunication links that ensure the rapid global exchange of observational data. Other observations, such as daily measurements of temperature and precipitation from surface stations worldwide are also transmitted via the GTS. This type of transfer and sharing of data makes rapid updates of data sets such as the Global Historical Climatology Network possible.

Other observational networks, such as the US Climate Reference Network, also take advantage of data transfer via NOAA satellites to a central processing center where they can be distributed via the GTS and internet. Some primary data transfers also take advantage of the internet. For example, NEXRAD radar data for many sites in the United States are transferred via internet file transfer protocols (FTP) direct to the National Climatic Data Center on a daily basis where they are made available to the public via the World Wide Web within 24 hours of collection. NOAA also heavily relies on a satellite-based system called NOAAPORT which uses a commercial provider of satellite communications to transfer NOAA satellite and ground based observations and other environmental data to information providers, such as NCDC, in near real-time.

More labor intensive methods for data transfer are performed by some members of the Cooperative Observer Program in the United States. Daily observations from some observers are transmitted through the use of telephone touchtone keypads. Other observers still rely solely on the U.S. Postal Service for transferring their daily measurements to NCDC. The full period of record for these data are online via NCDC's web site.

Addressing observational deficiencies

Although there have been dramatic improvements in observing systems and monitoring techniques in the past 10 to 20 years, observational deficiencies continue to be recognized and addressed. While the TAO/TRITON moored buoy array has greatly aided in forecasting developing ENSO episodes, the realization that year-to-year climate variations are also affected by ocean-related phenomena in other regions of the world has led to a greater focus on monitoring the oceans. As such, improving the global network of ocean observing systems is a continuing focus in NOAA, a major participant in the effort to increase the number of Argo observing floats on the world's oceans from 700 to 3000. These submersible buoys are designed to systematically measure the physical state of the upper ocean in near real-time, providing temperature, salinity and current measurements during 10 to 14-day cycles.

Improvements in land surface observing systems are also needed and are being addressed in several ways. As previously discussed, changes in observing equipment, techniques and environmental surroundings have threatened the integrity of the historical observing record. To ensure observations used for understanding climate variability and change are not affected by factors other than climate, a new U.S. monitoring network is currently being developed by NOAA. This network will provide the highest quality measurements possible at locations with stable environments, equipment and observational practices. When completed, the U.S. Climate Reference Network will consist of about 250 stations nationwide providing observations that will ensure a consistent record of the nation's climate, free from artificial biases caused by factors unrelated to climate.

Other efforts to improve monitoring and access to meteorological observations include a new National Weather Service (NWS) project to modernize the Cooperative Observing Network. This modernization effort will transition manual observing equipment to automated observing systems which will transmit observations in near real-time to NOAA and other users of weather information. Efforts are also underway in the NWS to improve observing equipment deployed as part of the existing Automated Surface Observing System (ASOS) sites at airports and national weather service offices.

A renewed emphasis by other countries throughout the world on developing observing networks that adhere to sound observing principles while also committing to making their meteorological data freely available is greatly needed. National Country participation in the Global Climate Observing System (GCOS) program will go a long way to ensuring the availability of reliable global climate observations.

These improvements in observations and monitoring are complemented by efforts to recover historical instrumental records stored in archives largely forgotten until recent years. NCDC's Climate Data Modernization Program (CDMP) was established to recover these historical records and transfer them from paper records and microfiche to digital databases. Over 30 million records have been rescued and made available online. These observations include many important climate related variables such as temperature, precipitation, snowfall, wind speed and direction, pressure, and cloud cover. This effort is nearing a stage where important sources of historic climate information will, for the first time, be available for analysis. These data will provide new insights into the range of conditions experienced centuries ago and will help provide new perspectives on how newly evolving climate patterns compare to those of the past.

Communicating climate information

While all of these advancements in observing systems and monitoring programs are vital to the continued progress toward better preparation and response to climate variations, these data and information are only truly useful when they are made available in a way that meets the needs of end-users. There has always been a close connection between data users and providers, and this connection has generally grown as technology has provided more options for improving communication. The growth of the internet has greatly simplified the process of providing data and information to decision-makers and most importantly has provided for its rapid dissemination.

In addition to methods for providing raw data, numerous interactive web sites now provide access to data and information that even the least scientifically inclined can understand and use for making observational analyses. Examples from the National Climatic Data Center include web pages for accessing U.S. and global daily and monthly maximum, minimum and mean temperature and precipitation data, snowfall and snow depth observations, U.S. climate normals, and several different drought indices and products for the US, Mexico and Canada. In the near future, the full periods of record for ISH, CARDS, and COADS (discussed above) will be placed online for easy access and retrieval. Various tools are also being developed to aid in the analysis, display, and graphing of these and other types of data.

As discussed previously, NCDC also provides published reports on U.S. and global climate conditions each month as part of its State of the Climate reports. These reports are prepared with a focus on making them useful for scientists, the general public and decision-makers at all levels of technical sophistication. The information is web-based and includes analyses of the various data sources to bring together in a single report, textual and graphical summaries which place the previous month's climate and weather in historical perspective. This information is useful for a wide array of interests including businesses concerned with assessing the impact of climate conditions on business cycles, public planners for understanding the status and potential impacts of drought at the local level, and forecasters for studying evolving climate conditions. Most reports are issued with an accompanying NOAA press release to ensure the widest possible dissemination of the monthly summaries.

Improvements in communication

Improving communication and data distribution, while remaining attentive to producing products in keeping with user needs, is a continuing focus within NOAA and much of the broader scientific community. Providing resources for ensuring improved seasonal forecasts and better use of climate data will benefit society through better planning, preparation and mitigation of adverse climate conditions. There continues to be a special emphasis on working with user communities to determine how observational analyses and products can be better tailored to their needs. Efforts are underway to improve interactions with the user community, e.g., through the upcoming NOAA/NESDIS Data Users' Workshop to be held in Boulder, Colorado June 11-12, 2003. Users of climate information include not only the private sector and the academic community, but also organizations within the US government. These include those involved in producing seasonal forecasts as well as other Agencies including Commerce, Energy, Agriculture, Interior, etc. Initiatives targeted at evaluating the climate needs of all users will help ensure the climate community is well positioned to effectively provide essential data and information during the coming decades of the 21st century.

Progress of climate science in providing information to prepare and respond to seasonal variations

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Question 1. Which observations support the identification of the El Niño/La Niña, what is the infrastructure that enables those observations, and what are the observational deficiencies?

The best precursor indicators for El Niño/La Niña are in the thermal structure of the upper ocean. The TOGA/TAO array has been an important source of observational data, leading to improved predictions of the onset of both El Niño and La Niña conditions. These data are important inputs into ocean data assimilation systems that provide initial conditions for coupled model forecast systems. However, at any given time some percentage of the buoys may be in need of sensor replacement or repair. The operational upkeep of the buoy array is critical.

Other critical observations include: the Argo broad-scale global array of temperature and salinity measuring profiling floats; drifting buoys; ships of opportunity; satellite measurements of sea level height and SSTs (TOPEX/Posiedon, Jason); the tide gauge network; atmospheric observations of the Southern Oscillation, tropical precipitation, and tropical surface winds. Because the El Niño/Southern Oscillation (ENSO) is an ocean-atmosphere coupled system, both oceanic and atmospheric parameters are important.

NOAA is playing a critical role in building a sustained ocean observing system for climate and ocean/marine services.

Deficiencies: If plans are implemented and funded, there should be few deficiencies. Analysis and prediction systems will need to assimilate these data and feed back additional needs, if any, regarding resolution, frequency, depth, circulation.

Question 2. How well do the models predict the time history of the El Nino/La Nina and associated phenomena on a global scale and do the model predictions capture the time scales adequately?

Unfortunately, statistical and coupled models are deficient in their ability to forecast the transitions from warm to cold and cold to warm in the ENSO cycle, and generally have little skill in forecasting the strength of individual events. Extremely strong events may be the exception. Some models are biased towards warm episodes, while others are biased towards cold episodes. The spread among the statistical and coupled model forecasts is sometimes "across the board" (warm, neutral, cold). Real-time monitoring and climate "nowcasting" based on experience provides enhanced guidance, which considers the statistical and coupled models' strengths and weaknesses.

No existing modeling technique captures the rapid evolution of conditions that are sometimes associated with intraseasonal variability, e.g., the Madden Julian Oscillation, westerly wind bursts, and oceanic Kelvin waves. This variability can have an important effect on the evolution (onset and decay) and strength of both warm and cold episodes. Numerical models offer the greatest hope for improvement in this aspect of objective ENSO cycle forecasting.

ENSO predictions seem to be episodic - good at times and incorrect at other times. Given good SST predictions, atmospheric models are capable of translating their information to reasonable probabilities of global impacts. SST prediction remains a key ingredient for accurate seasonal prediction efforts. It is likely a necessary, but not always sufficient, ingredient. This is the first link leading to global seasonal predictions, and hence, quite important. A coupled model, ocean data assimilation, and adequate hindcasts for past cases (at least starting from 1980-present) need to be well maintained and improved. Statistical model forecasts should become baseline tools to which we compare dynamical model forecasts, to prove the level of skill added by the dynamical models.

Question 3. How well are the weather and climate information communicated to response decision makers and what improvements should be made?

In regards to ENSO cycle forecasts, the scientific community often sends a mixed signal, which is hard for decision makers to interpret, even in a technologically advanced country such as the U.S. The problem is much worse for many developing countries. Standardizing our terminology can send clearer messages to the users. NOAA is working on some aspects of this standardization.

For the U.S a watch/warning system could be developed similar to that used by the NWS for other extreme events (hurricanes, tornadoes, winter storms). For example, An El Nino or La Nina Watch would be issued when conditions are favorable for their formation within the next six months. An assessment of the recent evolution and current conditions, together with forecast information, provided by statistical and coupled dynamical models, would be used to determine that a watch should be issued. The ENSO Diagnostic Discussion, which is a consolidated effort of NOAA and its funded institutions, could serve as the vehicle for disseminating Watch information. An El Niño or La Niña Warning would be issued once an event has formed, which will be determined using the NOAA definitions for El Niño or La Niña currently being revised. The warning should continue in effect until the event has ended. Different terminology is an option.

Historically, the intensities of El Niño episodes have been determined after the fact taking into account a variety of features, such as the magnitude and distribution of SST anomalies, magnitude of atmospheric indices (Southern Oscillation Index, low-level winds), duration of the event and strength of related impacts. Similar to the procedures used for classifying the intensity of tornadoes, an expert assessment team, composed of NOAA and non-NOAA scientists, could be established to determine the intensity of El Niño and La Niña episodes after each event has ended. Preliminary intensity assessments by the expert team could be made during an event, with the information being included in the ENSO Diagnostic Discussion and Climate

Diagnostics Bulletin. The expert team should be tasked with developing a suitable ENSO scale for classifying the intensity of events.

In addition to an ENSO Early Warning System, there are needs for improved ENSO Cycle Impact Assessments in real-time. In particular, one can use an official El Nino/La Nina Index (the All Nino Index or "ANI") being developed by the Climate Prediction Center(CPC) for NOAA, in conjunction with an index of ENSO impacts (such as the Tropical Precipitation Index proposed CPC experts) to put current conditions in the proper historical context (e.g., via scatter diagrams). These indices will be sent to NOAA scientists for feedback.

There is a strong need to develop strategies to understand linkages between leading patterns of natural climate variability (ENSO, MJO, AO) and weather extremes in models and observations, i.e., shifts in probability distribution functions (PDFs), since weather extremes are important to decision makers. This implies bringing the Numerical Weather Prediction, climate variability, and climate change modeling communities together.

Information sent to the public invariably creates some misconceptions, yet it may often be used by decision makers. Lack of clear communication between forecasters and users remains a significant problem. The relatively new National Weather Service (NWS) Climate Services Division, with a headquarters staff of about 10 lead by Dr. Robert E. Livezey, works closely with the CPC and the NOAA and external climate science and user communities to develop and provide NWS' and NOAA's strategic vision for climate services. It also develops policy and requirements for climate prediction products and other services related to periods ranging from week-two out to one year, including seasonal forecasts and hazards assessments. The division also sets NWS field policies and procedures for climate prediction products, defines service and mission needs, solicits user feedback to evaluate new products and services, and coordinates/approves final product design.

Question 4. What improvements are needed in observational, technological, and modeling capabilities to significantly increase seasonal predictive accuracy.

The discussion following Question 2 above applies here as well. Improved ocean observing systems and improved data assimilation systems, which lead to better analyses, are expected to provide improved initial conditions for model forecasts.

Modeling Capabilities

Improved modeling, simulation and forecasting of subseasonal variability is important for improving seasonal prediction. Often, one or a few short term extreme swing in subseasonal weather regimes make the difference between a seasonal forecast for average conditions being accurate or not. There are a number of key sources of unrealized predictability on subseasonal time scales including tropical heating, soil wetness, the Madden Julian Oscillation (MJO), the Arctic Oscillation (AO) and the Pacific/North American (PNA) pattern. There is a strong need to develop strategies to tap the above sources of predictability by focusing research, model development, and observation systems (new ones?) on subseasonal problems. (Practical applications: Cold Season – Pineapple Express events; west coast flooding; Warm Season – MJO modulation of hurricane activity).

We must improve our understanding of key physical processes that must be parameterized for more accurate simulations and predictions of warm season precipitation with coupled models. (Practical application: the North American Monsoon Experiment will observe and model the diurnal cycle of convection in complex coastal terrain. Improved understanding and modeling of the diurnal cycle is likely to dramatically improve warm season precipitation forecasts).

Improving "Official" Outlooks – the Human/Machine Mix

- Improved SST consolidation forecasts of NOAA's official El Nino/La Nina index (the ANI) are being developed.

- Objective forecasts of U.S. precipitation and temperature will be based on these improved SST consolidation forecasts.

- Automated, objective, and standardized verification of seasonal outlooks is needed (not manual verification using ~100 stations). Improved skill measures, e.g., Rank Probability Skill Scores, need to be coordinated and standardized across the operations and research communities.

- Better measurements of tropical fields, both oceanic and atmospheric (rainfall, surface winds, heat fluxes, sea level) are needed.

- Computer resource technology needs to focus on understanding climate variability and prediction modeling - models with reduced biases and better climates.

- In order continue motivating the above investments, better insight into predictability limits is needed.

Progress of Climate Science in Providing Information to Prepare and Respond to Seasonal Variations

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Question 1. Which observations support the identification of the El Niño/La Niña, what is the infrastructure that enables those observations, and what are the observational deficiencies?

- Monitoring: Routine observations of heat content, OLR, surface wind, sea level pressure, SST and sea level height in the tropical Pacific region all help in identifying ENSO conditions.

- Others can say more about the infrastructure that enables these observations.

- Observational deficiencies: The TOGA/TAO array seems to be adequate for the equatonal Pacific, except that salinity data are not available in real time for assimilation and prediction. A TOGA/TAO-like observational system is needed in the tropical Atlantic and the tropical Indian Ocean.

Question 2. How well do the models predict the time history of the El Niño/La Niña and associated phenomena on a global scale and do the model predictions capture the time scales adequately?

- Models are unable to predict the origins of ENSO. There is modest skill in predicting the evolution of ENSO, but only if the initial conditions already include a finite amplitude ENSO. Models are also unable to predict the correct phase and amplitude of SST anomalies.

- For the 1997-1998 ENSO case, no model could predict the evolution of large SST anomalies from January 1997 to July 1997. The models began to predict a warm event only after March 1997. By July 1997, one could see a major ENSO by visual inspection yet no model had predicted it. Predictions starting in July 1997 also could not predict that an exceptionally large ENSO was developing in spite of the fact that the initial conditions in July 1997 already had large SST anomalies.

- Society at large seems to have a false perception about our ability to predict and the degree of success in the prediction of ENSO.

- Our ability to predict the global effects of ENSO is even less than our ability to predict tropical SST anomalies and ENSO indices.

- It is somewhat unfortunate that in spite of a clear demonstration that ENSO and the associated global circulation is theoretically highly predictable, we have not been able to make the required progress in improving models and developing assimilation and initialization techniques for the coupled ocean-atmosphere system. Thus we have been unable to exploit the theoretical predictability for practical benefit to society. (More on this topic in response to Question 4)

Question 3. How well is the weather and climate information communicated to decision makers and what improvements should be made?

- Others can say more about this question.

- **For the specific case of India**, summer monsoon rainfall predictions are communicated to the highest levels of the government (Prime Minister, Agriculture Minister, Planning Minister, etc.). The statistical model used by India uses several ENSO indices as predictors. If a drought is predicted, large sections of the government take appropriate action to ensure the availability of diesel fuel to run pumps (needed due to the shortage of electricity), seeds and fertilizers, and food in the market to avoid hoarding and profiteering. An attempt is made to redirect electricity from urban areas to rural farmers. The agriculture ministries of different states activate crop-weather watch groups, who advise the farmers about the impending drought and suggest the timings for sowing and choice of seeds.

- **Monsoon rainfall prediction for 1997 (an anecdote)**: By May of 1997, it was clear that a major warm event was developing in the Pacific. US weather service scientists had predicted a monsoon drought. The Indian Meteorological Department issued a forecast of normal monsoon (this was their tenth consecutive prediction of normal monsoon rainfall). The Indian ambassador to the USA was informed by “US scientists” about the seriousness of the situation, who in turn conveyed the concerns to the Indian government, and some measures were taken by the appropriate authorities in India. But in spite of the presence of the largest warm ENSO event (and in contrast to all the observational evidence in the past 100 years), the monsoon rainfall was normal. (IMD forecasters had a good laugh and said “shame” on “US scientists”).

- **For the specific case of Brazil** (personal communication, A. Moura), the state of Ceara has a highly developed institutional infrastructure to take advantage of climate forecasts. Since ENSO is not the only major determinant of rainfall anomalies in Ceara (the tropical Atlantic SST dipole is also very important), Brazilian scientists make the overall prediction and bring it to the attention of the governor of the state. The state government takes appropriate action to utilize the labor force that becomes available because of reduced agricultural activities caused by droughts. Based on climate forecasts, the government suggests dates for planting. The banks are instructed to give special loans for seeds and fertilizers. It has been claimed that improvements in climate forecasts have helped the state of Ceara in better management of the state economy by assigning appropriate resources to the agriculture sector and the industry service sector. Whenever a major drought is predicted, the state makes a deliberate intervention to boost the industry/service sector so that the losses of agriculture sector are somewhat compensated by the gains in the industry/service sector.

Question 4. What improvements are needed in observational, technological, and modeling capabilities to significantly increase predictive accuracy?

- I will address the needs in modeling capabilities. Others can address the needs in observational and technological capabilities.

- **The single largest stumbling block in progress towards making better climate forecasts is the deficiency of climate models and data assimilation techniques**. Climate prediction must be an integral and essential part of climate model development. Thus, progress in developing realistic models for climate prediction, especially the ENSO prediction and the seasonal to interannual prediction, crucially depends on teamwork by a critical mass of qualified scientists engaged in model development and climate prediction. However, the climate modeling research in the US is scattered among various US agencies (and their respective research centers) in a way that is not conducive to progress, especially for prediction of ENSO and seasonal to interannual variations. For example, while NSF/NCAR have a large climate modeling and model development effort, they are not required to make climate forecasts. Therefore, there is no accountability to see if the model development effort is beneficial for climate prediction. NOAA/NCEP have the responsibility to make climate prediction, but are unable to establish a critical mass of talented people to build and improve coupled climate models for ENSO prediction. The modeling group at NASA/GSFC is primarily focused on the demonstration of the utility of space observations for climate variability and climate prediction. Other modeling groups like IRI and COLA have been instructed not to do model development and utilize existing models for climate prediction and predictability research. **Thus, USA lacks a single highly focused large effort in model development and dynamical prediction of ENSO and other aspects of short-term climate variability.** That one of the most profound discoveries of our field (existence of predictability beyond weather) has not given birth to an institutional infrastructure in USA that could provide the benefits of that discovery to society is quite unfortunate (and in fact tragic).

Research Potential for Improvements in Climate Prediction

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Twenty years ago the great 1982 El Niño event unfolded, raising the consciousness of both scientists and lay persons about El Niño and its climatic and societal impacts. A rather small subset of the climate research community was working on the problem of El Niño, and more generally atmosphere-ocean interactions. It is remarkable that the largest El Niño event on record to date was well underway before it was even detected. In the years since, very important progress has been made on several fronts: the theoretical – giving a conceptual understanding for how the coupling between the tropical atmosphere and ocean can give rise to El Niño and related climate phenomena operating on time scales from months to years, and how these tropical variations can express themselves on a nearly global-scale through dynamic processes in the atmosphere; the observational – through the conception, design, and implementation of targeted observation systems in the tropical Pacific that allow us presently to monitor conditions beneath the ocean surface on a daily basis; and the predictive – through the construction of models and prediction systems with demonstrated, if modest, skill in simulating and forecasting aspects of El Niño at lead times of up to several seasons. Despite the progress, a number of surprises have been encountered over recent years in forecasting El Niño and its larger scale climatic effects. These have led to new research questions, and an appreciation for a number of challenges yet to be addressed in the area of seasonal and longer term climate prediction.

Observations.

Critical upper ocean observations are now being made in real time in the equatorial Pacific ocean. These allow continuous monitoring of the state of El Niño, which provides in itself a basis for anticipating future conditions in many situations. But in addition, these measurements are being utilized for ocean data assimilation – that is, the process of initializing the ocean conditions for prediction models. In addition to these in situ observations, remotely sensed fields are being incorporated into current prediction systems with promising results; especially sea surface temperature, estimates of surface winds from the scatterometer instrument, and estimates of sea level from altimetry. Altimetry has not yet been fully exploited because to use sea level information properly there must be an ability to separate the effects of ocean temperature and salinity fields, and the latter are still not being measured routinely. It is noteworthy that the continuation of several satellite-based observations is not guaranteed into the future. To date, some of these products have been supported through NASA initiatives that derive largely from technology advancement, and not sustained climate observations. This underscores the need for all such observations to be managed and supported together with *in situ* observations, in a comprehensive sustained climate observing system (as recommended in several NRC reports and elsewhere).

Apart from the near-equatorial region serviced by the real time buoys in the Pacific, there is limited real-time information for either salinity or upper ocean temperature. According to our physical understanding of El Niño, the off-equatorial information contributes to the longer term predictability of the climate system, from perhaps a few months to a few seasons ahead. It will likely improve our ability to forecast El Niño at all lead times to have increased information of both temperature and salinity throughout a broader domain of the tropical Pacific. New observing systems, such as profiling floats, have been developed for this purpose. It is important that such systems be supported internationally. It is also important that the design of such systems be evaluated in the context of existing prediction models/systems in terms of potential to impact climate forecasts. This is a resource intensive undertaking, which should be explicitly budgeted and incorporated into proposed new observing systems/programs (in contrast to past practice where the issue has been ignored). It cannot be undertaken adequately by operational forecasting centers as part of routine activities, though these centers can provide needed infrastructure for such special assessments.

Real-time ocean observations outside the Pacific are also very limited. There is evidence from recent studies that ocean variability in both the other tropical basins is also important to seasonal and longer term climate variability in at least some regions. Enhanced monitoring of these regions is highly desirable. From present understanding, the importance of dynamic ocean processes of the extratropical oceans is expected to be less significant for seasonal prediction, and realtime monitoring of these regions could assume lower priority.

Current Predictions and Products.

There are currently a variety of methods employed routinely to predict El Niño, ranging from fully statistical models, to hybrid statistical-dynamical models, to complex coupled models with sophisticated data assimilation/initialization procedures. The current capability to forecast El Niño is roughly similar, and quite modest, among all of these methods, as estimated by correlations of observed and predicted large scale El Niño indices, over a period of years typically ranging from 10-20. One immediate problem is that shortness of records with which to validate the predictions, deriving from a lack of observations (especially ocean observations) that can be assimilated for earlier periods. As a result we do not have robust estimates of skill, but rather indications. Given this restriction, it is difficult to distinguish clearly the performance among the wide array of methodologies currently in use. The more sophisticated models and data assimilation systems are generally believed to have more potential for further improvement, but they are not clearly superior at present.

El Niño prediction skill has seasonal dependence. For all predictions, there is a preferential loss of skill when forecasting through the period March to May, relative to other times of year. This is believed to represent an inherent property of the climate system itself – that is, any sources of errors will tend to manifest themselves preferentially at this time of year. Such knowledge of conditional uncertainties in forecasts, relative to season or otherwise, is extremely important to the consideration of any potential use of the information.

Improved initialization of coupled model forecasts remains an important research topic for the future. Analysis of typical forecasts suggests that serious biases exist in most coupled models, such that straightforward initialization may introduce "shocks" in the model that compromise the ability to forecast the real signals of interest. One approach may be to develop ways to initialize the components (ocean, atmosphere, land,..) interactively, rather than the current common practice of separate initialization.

Predictions over the past decade have raised new questions about the relation between seasonal and both shorter and longer-term variability and predictability. During the early 1990s nature exhibited El Niño like fluctuations which departed from those in the earlier record; anomalies became much more persistent in the central Pacific (spanNiñg several years rather several seasons), and much more volatile in the eastern Pacific (displaying rapid onset and declines over just a few months rather than several seasons). The period proved much more challenging for forecasters than the preceding decade, where El Niño variations had been more regular. Yet other questions were raised from the 1997
El Niño, where the failure of virtually all existing forecast models to predict a very rapid and intense onset suggested the possible importance of episodic, week-to-week wind bursts in the western Pacific to the subsequent evolution and timing of the El Niño. These issues remain important research topics, and is some cases suggest new methodologies that may allow either better forecasts or better assessments of uncertainties in forecasts, or both.

An important finding is that when the results of several different forecast systems are pooled together, even in the simplest manner (say, an average), the overall performance is generally found to exceed that of all the individual systems. The concept of multi-model based forecasts is gaiNiñg popularity for this reason. Underlying this is the very reasonable hypothesis that each forecast system has various systematic errors, and that a multi-model based forecast has a better chance to represent the full range of possible outcomes than any individual model.

The issue of the climatic expression of El Niño and other seasonal climate phenomena worldwide has largely been pursued in parallel with El Niño forecasting proper. First, a number of important studies based on the historical data have highlighted statistically preferred seasonal climate anomalies in many regions, associated with El Niño and other phenomena. Numerous studies have documented the ability of current (atmosphere only) climate models to reproduce various of these observed favored patterns when "forced" with observed ocean surface conditions (including El Niño and other patterns). The overall results are mixed. Most models can simulate certain of the anomaly patterns in the vicinity of the tropical Pacific that are tightly tied to El Niño. Some of them exhibit skill in some of the more distant "teleconnection" regions, though this varies a great deal from model to model for each region. Finally, several models have been shown to exhibit very modest skill in forecasting aspects of surface temperature and precipitation based on predicted ocean temperatures.

The problem of forecasting the seasonal climate, or the statistics of weather within a season, is fundamentally probabilistic, due to the presence of internal chaotic variations (associated with the day to day weather) that often overwhelm the more persistent influence associated directly with El Niño or other climate phenomena. For dynamical models, the means to probabilistic forecasts is to utilize ensemble methods. Rather than a single forecast, many forecasts are made, either with slightly different initial states, or some other means of introducing tiny perturbations. The probabilities associated with specific outcomes of the seasonal climate can then be estimated directly from the ensemble results. Current forecast systems generally use such an approach, and indeed the best results are found with a multi-model "superensemble", for the same reasons as mentioned above for El Niño predictions. Skill levels vary greatly among regions, seasons, and models. Generally only small shifts in probabilities can be forecasted, and only for very limited regions, due to the inherent limited predictability ("noise influence") or model errors that mask signals actually predictable.

For many practical uses of climate forecast information, both spatial and temporal details are quite important. For example, for anticipating crop yields, the aggregate seasonal precipitation for a region may matter much less than the manner in which the total was achieved within each locale. This information is unavailable from global prediction models because they do not resolve either the spatial or temporal details adequately. Some methods of "downscaling" climate forecasts have recently been introduced, and in some cases are showing promise; for example in establishing more realistic local variability patterns associated with topographic effects, and in producing quasi-realistic weather sequences. Both statistical methods, as well as dynamical methods (nested regional models) have been investigated. Considerable further work is needed, in a variety of settings, to assess current methodologies and to identify the most effective approaches among the many options still unexplored. This is a priority area of research for tailoring climate forecasts to user needs.

Communication of forecasts.

It is noteworthy that, even during the most recent El Niño event in 2002, considerable ambiguity was found in forecast guidance from various forecast centers. This is the case despite the fact that common observational and forecast data were available to all groups. One key problem is that there is at present no common definition of El Niño; another is that the reliance on any single definition is limiting because El Niño comes in many different "flavors" with different influences on local climates. Within the auspices of international climate programs (CLIVAR) proposals have now been put forward to introduce a more objective El Niño "index", a continuous scale that is based on observed or forecasted ocean conditions. Adoption of such an index would certainly not resolve all ambiguities or uncertainty, but at least would establish a common basis for communication of information, akin to a Richter scale for earthquakes, or the category system that is used for hurricanes/typhoons. It would further allow regional forecast centers to provide more useful local interpretations of expected regional conditions without being hindered by definitions of what constitutes a noteworthy event in some global sense.

Another important issue in the communication of climate forecasts is that of probabilistic v. deterministic information. Due to the inherent sources of uncertainty climate forecasts will always be probabilistic in nature. To convey this, forecasts can be conveyed as either formal probabilities associated with specific conditions, or more generally as a set of forecast scenarios that are each considered possible. It will be useful for forecast centers to deliver a more uniform message on this topic, and to adopt some common protocols for forecast products. Initial efforts along these lines have been initiated within the international meteorological community. Where possible, target decision systems for which climate forecast information is being evaluated should be adapted to a multi-scenario framework where optimal use of information in the face of uncertainty can be formally explored.

Future Issues.

It is very likely that additional investments in observing more variables, over a wider domain, particularly the tropical oceans, should improve ability to forecast aspects of El Niño and other seasonal climate anomalies. A means to sustain valuable observations needs to be established among national and international programs/agencies.

Models undoubtedly can be further improved, but the process is exceedingly difficult and resource intensive. Good coordination among the few substantial development efforts can only be helpful, and the continued development of shared infrastructure to facilitate collaboration and technology transfer should be supported.

There is opportunity for substantial progress through the development of improved initialization strategies for forecast models, especially those that respect the interaction between components of the coupled climate system, and recognize rather than ignore the presence of systematic model errors. Additional attention should be given to land surface-atmosphere interactions, and to methods of initializing land surface conditions in forecast systems.

The methodologies that show greatest potential for future improvements – larger ensembles, greater spatial and temporal resolution, tailored forecast products, more elaborate assimilation systems – all place serious demands on existing human and computational resources. As the collective appetite for climate forecasts grows, and the impetus for intensified research is realized, it is important to similarly expand the resources to support these efforts.