

SEASONAL CLIMATE PREDICTION — STATUS AND PROSPECTS

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Several methods of seasonal climate prediction are now being used to forecast variations of surface temperature and precipitation. An international investment has been made to describe the El Niño/Southern Oscillation (ENSO) and to understand the dynamics of interaction within the tropics and with the extratropical circulation. The payoff to this research investment is a new capability for climate prediction and an opportunity to apply these results for national benefit. The methods that have been developed are based on both empirical studies and coupled ocean-atmosphere numerical prediction models.

This year the U.S. National Weather Service concluded a forty-year record of seasonal forecasts based on historical analogues and subjective experience, and commenced a new monthly series of long-lead Climate Outlooks, extending out to a year in advance. These outlooks are constructed from three distinct forecast tools. The method allows new results to be incorporated from research results in experimental forecasting. The Outlook is distinctly different from conventional weather forecasts; climate prediction is described by: (a) probability forecasts in three categories; (b) a minimum lead time of two weeks, out to a year in advance; (c) a minimum threshold of estimated skill; and (d) geographical and seasonal variation of skill.

Although these operational products are now being applied to the territory of the United States, the forecast methods have general applicability to other parts of the globe where sea surface temperature or soil moisture may have a sustained influence on climatic fluctuations. Experimental forecasts are now being made or planned by several countries; for example, for northern Europe, Africa, South America, Pacific Oceania, and South-East Asia.

The development of objective climate prediction presents a really new opportunity for practical climate applications and services. The proposed programme in Climate Information and Prediction Services (CLIPS) is focused on the primary thrusts of the Integrated Plan of the World Climate Programme. Climate prediction — along with current climate monitoring, the rapid distribution of climate information through international networks, and the traditional use of climate datasets — are valuable steps towards increasing economic benefits, reducing economic uncertainty and the risk of investment, and mitigating adverse impacts of climate fluctuations.

The future prospects for seasonal climate prediction lie with the national Meteorological and Hydrological Services (NMHSs) and their skill in developing economically valuable applications from climate analyses and predictions, as well as from climate datasets. At the level of commercial applications and societal decision-making, there is little distinction between climate services and the products of traditional meteorology and hydrology. Moreover, the vitality of the effort is strengthened by expanding this capability for weather and water, as well as climate. This is an opportunity for NMHSs.

INTRODUCTION — LIVING WITH CLIMATE RISK

In some parts of the world, we have come to accept that we are insulated from threatening variations in weather and climate by our modern, industrialized life. However, that perception is at best a transient illusion. In other parts of the world, climate variability and hazards are a constant and conscious risk to social life and to economic well-being. Furthermore, many successful commercial concerns now centre around the importance of climate anomalies in their global markets — everything from natural resources and cultivated crops to marketing. Figure 1 presents the world as it really is: an environment of risk within which we conduct our national and commercial activities.

The World Meteorological Organization (WMO) has accepted a prominent role in addressing the concerns of natural disaster reduction (Obasi, 1994), where it was estimated that 85 per cent of the worldwide disasters of the past 24 years can be related to weather and climate events. Losses in property and lives are staggering and appear to be increasing. Bruce (1994) estimates that disasters related to

hydrometeorological causes are 90 per cent of the total affected population of more than two billion people during the past three decades. In the United States, Changnon and Changnon (1992) estimated losses of US\$ 566 billion over a 40-year period. For these reasons, Riebsame (in Kates, Ausubel and Berberian, 1986) identifies climate as a potential hazard, as well as a context and determinant for human events, and as a natural resource. Maunder (1986) argues that climate is a unique and special (elite) resource. Thus, the physical climate system is simultaneously a potential hazard and a unique natural resource, and society also needs to develop an awareness of the full range of factors affecting the economy and influencing sustainable development (White, 1994).

What is to be done? Heretofore investigations into the issues of climate risk and impacts have focused on the historical record as a resource for understanding past events and preparing for the future (Mitre Corporation, 1980). Climate was thought of as the history of weather.

Today I would like to present a different point of view; namely, that climate is the future expectation for weather.

Climate is defined for time-scales beyond the limit of deterministic weather prediction (Landsberg, 1983; R. M. White in Mitre Corporation, 1980), or generally about two weeks. For the purpose of this presentation, climate prediction ranges from weeks to seasons, with the focus on seasonal climate variations.

As a result of a decade of rather intense research into the Pacific *El Niño*/Southern Oscillation (ENSO) with the Tropical Ocean and Global Atmosphere (TOGA) programme, the U.S. National Weather Service, Climate Prediction Center (CPC) is now beginning a new effort to predict climate operationally for specified seasons and at selected regions of the globe. This effort is motivated not only by increased scientific understanding and the cooperative collection of global data in the atmosphere and ocean, but also by a professional hope to really make a difference to the economic and social world in which we live. The capability to predict climatic variability, aside from climate extremes and trends, would be a major step towards meeting the threat of climatic hazards to which each nation is exposed.

At this point I would like to step back to acknowledge three scientists who have personally affected my view of the developments that have brought us to this point. First of all, Helmut Landsberg, former president (1969–1978) of the WMO Commission on Climatology, at an early date recognized climate as a natural resource (Landsberg, 1946). However, we no longer believe that the climate resource is unchangeable or inexhaustible, and the value of this global, natural resource is recognized to be even greater than before. It is somewhat surprising, but prescient that Professor Landsberg, as climatologist, addressed Ninth Congress in 1983 on the subject of "The Value and Challenge of Climatic Prediction" (WMO, 1983). Therefore, it is a personal pleasure to deliver today's lecture and to provide a historical extension to the subject of climate prediction. Twelve years ago climate prediction was addressed from the viewpoint of persistence forecasts, and "forecasts without time" (climatology), and the concept of climate regimes was described by synoptic air mass analysis. Today we are prepared to accept "brute force" methods of numerical weather prediction to predict climate variations. On the other hand, Professor Landsberg would be pleased to see that our methods are also based on empirical analysis of the historical climate record.

Secondly, I would like to acknowledge the influence of Jerome Namias who has carried this field as a blend of art and science for many years (Namias, 1964; 1968). He recognized the importance of ocean temperatures on the atmosphere and surface climate, and he led the development of seasonal weather outlooks at the U.S. National Weather Service about 35 years ago. Today, I am pleased to be part of the effort at the U.S. National Weather Service, Climate Prediction Center (CPC) to take the next step in the development of the vision that he had for long-range weather prediction.

Finally, I acknowledge the early and original work of Edward Epstein (1969), my first teacher in meteorology, who attempted to predict climate conditions directly with derived stochastic-dynamic equations. That effort, while not practically successful, inspired the curiosity of scientists to investigate the causes of short-term climate variations.

Returning now to the subject of the current status of climate prediction, we are compelled to recognize the optimism for ENSO prediction and the use of numerical techniques. Latif, *et al.*, (1994), in a review of current prediction schemes in the early 1990s, asserted that significant capabilities were at hand for climate prediction at lead times exceeding a year. McPherson (WMO, 1994) reported on new numerical results and ensemble forecasting techniques that would lead to multiseasonal predictions of climate anomalies. Recently, model results for the prediction of sea-surface temperature (SST) eighteen months in advance have been presented (Kirtman, *et al.*, 1995).

However, in spite of this optimism, climate prediction is a tough problem. Numerical weather forecast models running in conjunction with ocean models must be run repeatedly to establish skill beyond natural variability (Kumar and Hoerling, 1995). This is an expensive effort and it requires extensive evaluation by research personnel. Furthermore, good results are sensitive to model climatology and internal parameterizations (Kumar, *et al.*, 1995). Finally, Pacific/ENSO conditions during the past five years have been more difficult to predict due to short-term ocean variability (Ji, Leetmaa and Derber, 1995; Wang, 1995) and possibly due to decadal trends in the ocean.

Therefore, this presentation will describe an operational climate forecast system that takes full advantage of empirical techniques, as well as new results from physical (numerical) models. This forecast methodology is a radical departure from the former methods, but it does not now solve the climate prediction problem. It is the beginning of a long path towards the development of effective climate prediction tools of different sensitivities and capabilities. The current status of climate prediction has been comprehensively reviewed by Palmer and Anderson (1994), and a review of prediction models was done by Latif, *et al.* (1994). A description and comparison of the seasonal ENSO prediction is given in a review by Barnston, *et al.* (1994).

The discussion (section on seasonal climate prediction) of operational seasonal prediction for the territory of the United States is preceded by a brief review of the importance of ENSO and other physical mechanisms, and is followed by a discussion of the prospects for seasonal climate prediction. The consequences (section on applications) of climate prediction are climate applications and services, and a vision is presented for the development of an international programme called Climate Information and Prediction Services (CLIPS). At the level of applications, however, the user does not distinguish between weather, climate, and hydrology. Therefore, this is an opportunity for national Meteorological and Hydrological Services (NMHSs) to support a new and developing effort in climate prediction and its application to practical economic questions and social policies.

To launch this new vision of the meaning of climate (the expectation for weather), to sustain the effort to predict climate variations with lead-time and skill, and to deliver on the promise of practical applications, it would be well to recall the words of Robert M. White, former Administrator of NOAA, member of the WMO Executive Council, and Chairman of the First World Climate Conference:

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What is it that we wish to do? Ultimately we wish to improve the effectiveness of the use of climatic information in decision making so that we can increase the efficiency of economic activities, improve economic and social planning, and protect life and property against climatic hazards (from Mitre Corporation, 1980).

EL NIÑO/SOUTHERN OSCILLATION (ENSO) AND OTHER DIFFICULTIES

The increased expectation for seasonal climate prediction currently lies in an analysis of global impacts of sea surface temperature variations in the tropical Pacific; i.e. the *El Niño*/Southern Oscillation (ENSO). The global impacts have been determined in a classic analysis by Ropelewski and Halpert (1987; 1995). Figure 2 is a summary of simultaneous climate impacts in the winter of the northern hemisphere. Although the impacts in surface temperature and precipitation anomalies are well defined in the tropics, there are also important signals in the middle latitudes of both hemispheres, particularly in North America. For example, on the Gulf coast during ENSO winters (October March), there is a 70 per cent probability of receiving greater than median precipitation, with opposite conditions during the ENSO cold phase. The median precipitation ranges from 325 to 450 mm over the range of ENSO conditions, with a normal value (over the base period) of 380 mm. Thus, this is a significant signal in North America, and it is even stronger at some tropical stations.

ENSO conditions are now monitored through a network of buoys, ships and satellites, and the fields are analysed and reported in near-real-time. The current conditions of sea-surface-temperature (Figure 3) show recent (April 1995) mean SST and anomalies at the conclusion of a six-year period (1990–1995) of warm surface temperatures with only a brief interruption during 1994. However, in order to predict ENSO conditions, it is also necessary to monitor and relate surface conditions to the temperature and motion throughout the upper ocean, such as described in Figure 4. There is a dramatic difference in the structure of the upper ocean, as well as in the surface temperature, during the warm phase of ENSO, and also during the cold phase (1988–1989).

These are the conditions in the tropical Pacific Ocean that are most important for predicting seasonal climate anomalies both in North America and elsewhere around the world. A good summary of the ENSO phenomena has been given by Enfield (1989), and a summary of ENSO/SST prediction studies is given in Latif, *et al.* (1994) and Barnston, *et al.* (1994).

These ocean surface anomalies are partly responsible for the global climate anomalies described above. Some graphic examples of a composite signal from the tropical Pacific in surface temperature (°C) and precipitation (mm/month) are shown on a global scale for March in Figure 5. This result is constructed from a simple composite keyed on the equatorial Pacific SST extremes above 0.5°C at the date line (Coupled Model Project, 1995). When the global composite anomaly is analysed month-by-month in North America (Figure 6), the seasonal variation is clear in temperature and precipitation.

While ENSO is the primary motivation for seasonal climate prediction, the ocean surface temperature in other parts of the tropics is also important, and to a lesser extent, the extratropical oceans as well. In fact, deep ocean currents are part of decadal variations in the oceans that appear eventually as a component of the observed sea-surface temperature anomaly and, subsequently, are important for forcing an atmospheric response. For example, Latif and Barnett (1994) have recently identified decadal variations in the Pacific subtropical gyre that could account for slow variations in ENSO, and subsequently, in atmospheric climate variability. An example of slow variations in the atmosphere can be seen in the 850 hPa wind record in the tropical eastern Pacific during the past two decades (Figure 7). Both the ocean and the atmosphere seem to contain slowly varying components that determine the global meteorological climate.

In addition, there are several other physical mechanisms that also contribute to the observed climate variability that we hope to forecast. Although these mechanisms are contained implicitly in historical data or physical models, their value to prediction may increase as we learn how to include some of them explicitly. First of all, global scale, intraseasonal oscillations with periods in the range of 40–60 days (M-J oscillation, as reviewed in Madden and Julian, 1994) modulate convective processes in the tropics.

Secondly, conditions at the lower boundary of the land surface are also important for seasonal prediction; in particular, soil moisture and the extent of snow cover. Furthermore, although the topography is static, it is also an important mechanism for determining the particular regional response to other large-scale forcing of the climate system through the action of jet stream anomalies, for example.

Of course, climate forcing and response must be forecast within the context of natural variability in the atmospheric system that includes a great deal of chaos as well as organized synoptic storms, small-scale, intense convective disturbances, and hurricanes and typhoons. Madden (1976) and Chervin (1986) have showed how difficult it is to detect the background climate signal above natural variability, but there are techniques being developed to improve the chances of seasonal climate prediction even within a meteorologically-noisy atmosphere.

Finally, it is recognized that ENSO is not a regularly recurring event. The concept that global climate change could influence the ENSO mechanism, or could modify the mechanism by which ENSO/SST fields influence global climate anomalies in the atmosphere has not yet been confirmed (Knutson and Manabe, 1994).

SEASONAL CLIMATE PREDICTION

Based on the experience of the last four decades of preparing seasonal outlooks with zero lead-time, on new research results on ENSO coming from the TOGA Programme, on outstanding computer and modelling resources, and on a global, *in situ* and remotely-sensed and cooperative data collection system to monitor ENSO and its global impacts, it is now possible to attempt seasonal climate prediction at some locations and for selected

seasons. Beginning in January 1995 the U.S. National Weather Service commenced the production and delivery of a new, long-lead *Climate Outlook*. This product is produced monthly, with a minimum lead-time of two weeks, and extending out to a year in advance. The target area is the United States, including Alaska and Hawaii.

This new seasonal climate prediction is one of a suite of three climate guidance products produced by the National Centers for Environmental Prediction (NCEP) at the Climate Prediction Centre. The suite of products is shown schematically in Figure 8: Week two, monthly, and seasonal outlooks. Although all the products generally lie outside the range of deterministic weather prediction, the global medium range forecast (MRF) model of NCEP is the primary tool for producing Week two forecasts.

We can assume that the seasonal forecast will be generally beyond the influence of initial conditions, and a combination of empirical forecast tools and physical/numerical forecasts are utilized to produce the operational product.

An empirical basis for seasonal forecasting

The primary empirical forecast tool now used at NCEP is canonical correlation analysis (CCA) that was developed by Barnett and Preisendorfer and applied to an operational forecasting of SST by Barnston and Ropelewski (1992), and to North American temperature and precipitation by Barnston (1994). This method is a statistical, pattern-recognition technique that was developed on concurrent data from 1955–1991. The predictors are fields of global SST, 700 hPa height fields in the northern hemisphere, and antecedent temperature and precipitation in the target areas of the United States.

The forecast of SST in a region of the eastern tropical Pacific using the CCA method is shown in a time-series in Figure 9. Since 1990, the Climate Prediction Centre has been publishing this ENSO/SST forecast in the monthly *Climate Diagnostics Bulletin*. This forecast is imperfect, but compares favourably with the results from a simple, ocean-atmosphere coupled model of the equatorial zone by Zebiak and Cane (1987) and from the NCEP Coupled Model Project (Ji, Kumar and Leetmaa, 1994a, b). However, improved physical models are already claiming skill for SST forecasts out to lead times of 18 months (Kirtman, *et al.*, 1995).

The CCA forecast method is applied to North American precipitation and surface temperature (Barnston, 1994) and is intended to be the primary empirical tool that is sensitive to ENSO variations. However, because it is based on a limited period of historical data, this method has not been able to predict extreme conditions. On the other hand, the CCA method provides a solid (conservative) basis for long-lead seasonal outlooks.

The second empirical tool that is used is optimal climate normals (OCN) developed by Huang, Van den Dool and Barnston, (1994). This method is based on 60 years of historical climate data in the United States. Predictors are surface temperature and precipitation. The period for which the historical "normal" was the best predictor was identified as a function of season and location (Figure 10). However, as a practical matter, a period of 10 years was chosen for all

locations and seasons. Thus, the OCN method is able to account for some of the recent climatic bias in the forecast variables.

Physical models as forecasting tools

A number of different ocean-atmosphere coupled models have been developed to explore the possibility of seasonal climate prediction. An equatorial model of intermediate complexity by Zebiak and Cane (1987) has established the principle. Subsequently, Barnett, *et al.*, (1994) at the Scripps Oceanographic Institute in the United States developed a global forecast model with collaborators in Hamburg (Latif, *et al.*, 1993). Brakovic, Palmer and Ferranti, (1994) at the European Centre and Ji, Kumar and Leetmaa, (1994b) in the United States have also reported accomplishments from coupled model experiments. Clearly, this research is an international effort with implications for the entire world, and not just in the United States alone.

At the NCEP of the U.S. National Weather Service a coupled ocean-atmosphere model (Ji, Kumar and Leetmaa, 1994a) is used as a forecasting tool for input to the development of an operational seasonal climate outlook. The ocean component of the model was developed at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton University. The version used at NCEP now covers just the Pacific Ocean from 45°S to 55°N. With 28 vertical levels, the zonal resolution is 1.5°, and the meridional resolution is 1/3° at the Equator, increasing to 1° at 20° poleward in both hemispheres.

The atmospheric model is the operational global medium range forecast (MRF) model used at NCEP with a vertical resolution of 18, and a spectral resolution of T40. The model has been modified to simulate more accurately convective processes in the tropics (Ji, Kumar and Leetmaa, 1994b).

The model forecast is made in a two-stage process. Monthly coupled forecasts of tropical Pacific Ocean SST are made out to 13 months in advance using an atmospheric model physically coupled to the ocean. A bias error is removed from the SST forecast fields which are subsequently used to produce an ensemble of nine atmospheric forecasts for surface temperature and prediction out to seven months in advance.

This technique is still under development, and there will be further changes to the methodology as well as to the physical parameterizations.

Some results for a composite ENSO/SST forcing are shown in Figure 11 during October (top) and February (bottom). In addition to a composite forcing, a more extreme case (labelled major warm ENSO) was used in which the mid-Pacific temperature anomaly was greater than 0.8°C. While these results are encouraging, they show results that are seasonally dependent. For example, a warm tropical SST is associated with a large cold anomaly in the fall and a warm anomaly in the spring. The lower right panel in both seasons shows that the anomalies of the past 15 years are similar to the composite (ENSO) response. This secular change may be part of a decadal drift in oceanic forcing.

It is even more difficult to use the coupled model to predict specific results season-by-season. In Figure 12,

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the results for early 1988 are shown during the development of severe drought conditions in the Midwest United States. On the other hand, during the present year (1995) on the West Coast of the United States, accumulated precipitation was extreme in January. Although the coupled model was unsuccessful in predicting this event under operational forecast conditions, there are encouraging results in the global geopotential height field (Figure 13) in North America when the model is forced by the composite ENSO/SST. Likewise, there are some similarities in the predicted and observed precipitation fields (Figure 14) in the western United States.

In general terms, when the coupled model forecast system is run on historical SST data, it compares favourably with other methods and correlates in the range of 0.6–0.9 in forecasts of SST (Barnston, *et al.*, 1994). Even with accurately predicted SST, however, it is a much larger step to predict climate anomalies accurately in North America. The verisimilitude of a climate model with the atmosphere is more demanding than for a short range weather forecast model, and small changes in the model physics can give substantially different results (Kumar, *et al.*, 1995). Nevertheless, by using the coupled model as one of the forecast tools, we are in a position to take full advantage of new successes soon after they occur.

An operational climate prediction product: *Climate Outlook*

The forecast tools described above are now used once each month to produce regularly and routinely a new seasonal climate forecast product for the target area of the United States, including Alaska and Hawaii. These forecasts (Figures 15 and 16) have several important qualities which should be emphasized:

- (a) Probabilistic: The forecasts are for seasonally-averaged surface temperature and precipitation in a probabilistic format; i.e., the probability in each of three categories: above normal, near climatological mean (temperature) or median (precipitation), and below normal, as defined in Figure 15b;
- (b) Skillful: Each forecast tool is evaluated with historical data, and skill levels are determined at all locations by cross-validation or equivalent tests for physical models. A minimum threshold value of local skill is imposed corresponding to an anomaly correlation of 0.3. In areas where all forecast tools have insufficient skill, no forecast is made. In that case, some form of climatological forecast is recommended;
- (c) Objective: All forecasts are evaluated simultaneously and concurrently with skill maps for each season of three months. The goal is to combine linearly these results to create an objective, consolidated forecast as a reference for the human forecaster. At the present time, the forecaster uses the objective forecast from each forecast tool with the accompanying skill values to produce a single operational forecast;
- (d) Long lead: Each forecast tool has somewhat different skill characteristics, depending on season and location. In many cases, positive skill extends out to multiple seasons in the future. The skill associated with numerical weather prediction within the first two

weeks is not permitted to influence the seasonal climate forecast. For these reasons, the suite of seasonal outlooks begins with a minimum lead time of two weeks for the first forecast product. This is followed by a succession of seasonal (three month) forecasts, each with a lead time of an additional month. The last forecast map covers the period of month 13, 14, 15 (a year in advance of the first map) with a lead time of 12.5 months (see Figure 16a, b);

- (e) Conservative and progressive: By using a methodology that combines separate forecast tools (and is open to additional information), new research results, for example from complex coupled models that have established skill in a historical context, can be easily included to improve the operational product. On the other hand, as the conflicting claims from experimental forecasting are sorted out, the *Climate Outlook* provides a solid empirical base for seasonal climate forecasting and a framework for adding the results of dynamic model forecasts. Both ENSO influences and some aspects of interdecadal climate trends can be accounted for in the present forecasting method. The prediction of extreme and unusual events not already encountered in the historical dataset, must depend upon new techniques based on physical models;
- (f) Accessible: The *Climate Outlook* is distributed through the normal channels of the National Weather Service, and is no longer published in hard copy for mail distribution. However, the full range of products, including forecasts from each of the tools as well as their skill evaluation is available from the Home Page of the Climate Prediction Centre/NCEP via Internet (Figure 17). The address is shown in the figure.

Skill evaluation

What is the character of the skill that is available from these long lead climate outlooks? Forecast skill values depend on the season and on the lead time. Since we are presented with the opportunity of making forecasts once every month, we will need a decade of experience before we can judge the results on truly independent data. On the other hand, each of the forecast tools has been evaluated over the past historical record, and this is our best estimate of future behaviour.

For example, Figure 18 displays the historical skill of the CCA method for seasonal temperature forecasts over the continental United States for long lead times as a function of the forecast season. During the late winter, and mid-summer there is only a small value of skill. However, in the winter, substantial skill is apparent, and the lead time can be extended to six months with little reduction in skill. Further refinement may be achieved by applying the method to a more limited region.

When the forecast is evaluated by region (Figure 19), areas of higher skill can be defined. There are several seasons when the skill of the CCA method is sufficiently large and of a duration suitable for long-lead forecasts. The strategy for operational climate prediction is not only to seek improvement in skill and to increase the lead time, but also to provide a framework to accept new

forecast tools from experimental predictions that demonstrate an independent and complementary record of skill with respect to lead time, season, and geographical region.

Of course these methods can be applied in other parts of the world as well. Some experimental work has been done by Johansson, *et al.*, (1995) for northern Europe, and the results are presented in Figure 20. This shows that the lack of an obvious ENSO signal does not prevent a potentially useful seasonal forecast. On the other hand, the results for Hawaii (Figure 21), closer to the ENSO signal, display an entirely different configuration. In this case, modest skill is available for lead times out to a year for all seasons.

Finally, these figures emphasize that the intrinsic climatic variability requires that seasonal forecasts be probabilistic and always uncertain. These specific skill results are unique to the CCA method; other forecast methods have different skill characteristics. When these forecast tools are judiciously combined and applied to specific seasons and locations, there is some optimism for seasonal climate prediction, even with long lead times.

PROSPECTS FOR CLIMATE PREDICTION

By comparison with the vision of Landsberg (1983; WMO, 1983), the past decade has turned up many exciting prospects for seasonal climate prediction. Although the concepts that Landsberg enunciated are still generally valid, I think he would be surprised at the progress that has been made in identifying atmospheric teleconnections and in describing slow variations of the climate system. He would be pleased at our efforts to create practical forecasts with our knowledge, and he probably would be critical of any attempt to overstate the capability of complex, coupled numerical models to predict climatic conditions.

At this time, there are many groups that are taking the next step beyond research investigations, and testing new techniques of experimental climate prediction. Some of the results of these efforts are published quarterly in the *Experimental Long-Lead Forecast Bulletin* (Figure 22). A casual reading of the table of contents shows a respectable collection of international contributors.

Coupled ocean-atmosphere models

The power and relative success of the coupled model experiments are impressive. However, the practical task of prediction is formidable. During the past five years of the lingering ENSO warm episode, none of the current models have performed favourably (Ji, Leetmaa and Derber, 1995). In addition to the ENSO signal, practical forecast methods must take into account decadal changes in the ocean. In particular, we should acknowledge that the unusual conditions during the flood of 1993 during the summer in the Midwest United States, and the extremely wet conditions in the western United States during the winter of 1995 were not predicted.

First of all, conditions of the upper ocean need to be forecast accurately before climatic forecasts in mid-latitudes can hope to be successful. Higher frequency fluctuations may be difficult to forecast, and this will degrade the forecast of climate variables and reduce the

lead time. Secondly, Kumar, *et al.* (1995) have shown that results from the coupled model are extremely sensitive to physical parameterizations and to the mean state of the climate model.

The prospects for seasonal forecasting using coupled models remain an open question (Kumar and Hoerling, 1995) because of the existence of substantial natural variability. The use of ensemble prediction techniques is a way to overcome low frequency, large-scale atmospheric "noise" in the model and as it occurs in the real atmosphere. Figure 23 shows the kind of variations in circulation that can occur during a long integration, even with a specified SST. A whole new technology (time lagging; singular vector analysis; and breeding of growing modes) is being investigated to learn how to create an ensemble and how to interpret the results for the time-scales of extended range forecasting (Toth and Kalnay, 1993; Tracton and Kalnay, 1993; Molteni, *et al.*, 1995). Similar techniques need to be developed for the long runs required for seasonal climate prediction (Toth and Kalnay 1995) where uncertainty in boundary conditions needs to be incorporated into the uncertainty of the forecast.

Climate regimes

This topic has become more interesting since the days of F. Baur because of a new understanding of chaos theory and the volumes of data available from model output. Although the concepts are quite clear (Molteni, Tibaldi and Palmer, 1990), they are difficult to put into practice (Mo and Ghil, 1988). However, these concepts open the possibility of forecasting the period of a climate anomaly, as well as its magnitude, with both in probabilistic terms. The value of such new forecast information was seen more than a decade ago by Landsberg (1983).

Simplified dynamic models

One of the first successful models of the ENSO mechanism has been a simplified physical model (Zebiak and Cane, 1987). There is a certain appeal to the use of simplified or intermediate models that describe the essential physics under consideration.

For example, Li and Wang (1994) have developed a thermodynamic climate model for coupling with an ocean model of intermediate complexity (Wang and Li, 1995). The resulting dynamical system simulates chaotic cycles that may explain seasonal variations in ENSO (Chang, *et al.*, 1994).

Another approach is to return to an implicit formulation of an ensemble on time-averaged equations (Epstein, 1969) and to seek an entirely different approach from the direct, but computationally-massive investigations of ensemble predictions with a coupled model.

Empirical models

Empirical, statistical methods have a long history and continue to serve as the standard by which more complex, physical methods are compared. In addition to CCA and OCN techniques, the current methodology of seasonal climate prediction encourages other independent methods to be developed, e.g., discriminant analysis or neurological networks. New methods can be incorporated into the

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- (b) It is successful and a leading pre

operational forecasts after sufficient skill has been demonstrated. The variety of original approaches and methods is presented in fully half of the current experimental forecast methods (Figure 22, bottom).

In one example, Van den Dool (1994) recognized that naturally occurring analogues are not generally available in the short historical record, but as a practical matter, analogues may be constructed artificially to determine seasonal climate anomalies. In this case (Figure 24), the SST forecast for a two-season lead is made from an artificially-constructed analogue using a historical resource (1956–1993) of global SST data to achieve a correlation as high as 0.9 in the Pacific region for the lowest mode (Van den Dool and Barnston, 1995). The skill using the complete analogue description for the period 1982–1993 is comparable to the results obtained from more complex physical models.

4.5 Intraseasonal oscillations

Of course, not all the climate variations in the atmosphere are produced by ENSO/SST. The M-J oscillation (Madden and Julian, 1994) is a planetary scale wave centred on the tropical belt, with periods in the range of 40–60 days. It strongly modifies or interacts with convection in the tropics. Figure 25, from Kousky and Kayano (1994), shows the velocity potential and convergence at 200 hPa for the first analysed mode of this oscillation that explains over 13 per cent of the intraseasonal variation. The slow progression and the vertical/spatial/temporal coherence (Madden and Julian, 1994) can be tracked over long periods of time, and this makes intraseasonal variations an important mechanism for seasonal forecasting in the tropics, sometimes modulating monsoons and ENSO variability; consequently, it can be important for prediction in the extratropics as well.

APPLICATIONS

The future of climate services

Climate applications and services have traditionally been defined as the resourceful analyses of historical climate datasets used to guide decisions for industry and commerce, especially in agriculture, water resources, and engineering design. In addition, the direct application of historical climate data has been used on a variety of tasks: to settle legal disputes, to estimate design conditions, and to aid planning and economic development, to name just a few.

During the past decade, there have been several important advances that have changed the way that climate services are conceived. The first advance concerns three revolutionary changes in the field of climate and the delivery of climate information.

- (a) The improvement of communications and computer resources now permits monitoring of climate anomalies in near-real-time not only at land surface stations, but also in the stratosphere, ocean, cryosphere, and throughout the climate system;
- (b) It is now possible in a large number of cases to predict successfully the mean conditions of the atmosphere and ocean over time-scales of months to seasons with a lead time beyond the range of deterministic weather prediction (more than one week);

- (c) New methods to distribute rapidly climate products and information by means of global networks are now available to an extraordinary large number of users in Government, academic institutions, public media, and the private sector.

The second advance is a new awareness that climate monitoring and prediction of near-future conditions are essential information for commercial decisions and the development of social policies. Near-future conditions are meant to include monthly, seasonal, and interannual climate anomalies. Climate information is not simply a historical resource. Both empirical and physical models for prediction present the decision maker with a probabilistic and rational guide for future actions.

In an increasingly competitive marketplace, and with modern societies increasingly sensitive to environmental hazards in water resources, energy supplies, and agriculture productivity, a knowledge of future climate conditions is a key to successful adaptation, and in some cases, even survival.

The third advance is the recognition that international cooperation is needed to share the full benefits of our knowledge and prediction of the global climate system. Specifically, the data collected in each country of the world from the oceans and from satellite platforms are required input for monitoring, prediction, and the subsequent application that lead to socio-economic benefits. Furthermore, a successful international research programme (World Climate Research Programme (WCRP) and TOGA) has brought new understanding of the global climate system. The time has come to complete the payoff from years of investment in several successful research programmes.

Based on these changes and on conceptual advances, there is now an opportunity to redefine climate services as the delivery of climate information using contemporary monitoring information, the predictions of likely conditions in the near-term future, and the application of this information to agriculture, water resources, energy planning, natural resources management, transportation, commercial applications, including retail sales, human health and tourism. A successful programme of climate information and prediction services will appeal to users in national and local Governments, academic research, the public media, the private sector, and wherever social and economic decisions are influenced by climatic variations and trends.

Climate forecast information

A number of authors have described the value of climate information and climate data resources for applications to the practical world of economic decisions and social policy (Maunder, 1974; Mitre Corporation, 1980; Maunder, 1986; Kates, Ausubel and Berberian, 1986). However, much of this thinking was directed towards the use of historical data or near-real-time climate information for assessment or for addressing economic decisions in the immediate future. There is much to learn from these studies that can be applied towards the use of climate forecast information.

Weather and climate forecast information has already been used on a wide variety of commercial

applications surveyed in Murphy and Katz (1985). For example, a recent application of the seasonal forecast to the gas-heating industry was done by Lehman and Warren (1994). Changnon (1992) and Sonka, Changnon and Hoping, (1992) have studied the needs of agribusiness for climate predictions. These kinds of investigations are needed to bring the technical product of climate prediction to the marketplace where it will be usefully applied. The practical application of uncertain, probabilistic climate forecasts will require the use and application of decision analysis methods (Winkler, Murphy and Katz, 1983) and a linking of climate information with an understanding of economic forces (Zhukovsky, 1981). In a recent example, Gandin, Murphy and Zhukovsky (1994) were able to present the comparative value of historical climatological information and a climatological forecast (Figure 26). In this example, the economically optimum strategy (EOS) sustains a lower loss than either a strategy of blind belief in the forecast (BFS) or the use of a climate normals (optimum) strategy (NS and COS).

Climate Information and Prediction Services (CLIPS)

The World Climate Programme (WCP) is about to enter a new phase. Based on the Second World Climate Conference and subsequent actions of the United Nations Framework Convention for Climate Change and the Intergovernmental Meeting on the World Climate Programme, the forty-sixth session of the WMO Executive Council (June, 1994) approved four major thrusts of the new, interagency WCP (Figure 27). To meet the opportunity framed by the *Climate Agenda*, especially climate services for sustainable development, a new programme has been proposed for the World Climate Applications and Services Programme (WCASP).

The objectives of this programme within CLIPS are presented in Figure 28. Stated concisely, the objectives include:

- (a) To provide an international framework;
- (b) To develop a global network of climate centres;
- (c) To demonstrate value and benefits;
- (d) To encourage the development of operational climate prediction.

The CLIPS programme is an opportunity to really make a difference in the practical use of weather/water/climate information for the benefit of national economy and the development of social policies.

CONCLUSIONS

After a long history of development, the possibility of making regular and routine, long-lead seasonal climate predictions based on objective methods for some areas of the world is now at hand. A new forecast publication, *Climate Outlook*, is the consequence of an objective methodology that incorporates historical evidence of climate anomalies, climatic drift, and the most recent results from ocean-atmosphere coupled models. Seasonal outlooks are presented in probabilistic terms with accompanying skill levels and lead times out to a year in advance. This effort is the beginning of a long-term effort, not a crowning achievement, that will extend the use of climate information into the future with probabilistic

forecasts with a substantial lead-time and accompanied with an evaluation of skill. In this sense, climatology has changed from a historical perspective to expectation for future weather conditions.

The operational framework for constructing seasonal climate forecasts is designed to incorporate new, experimental climate prediction methods as they are developed. For this purpose, a special quarterly publication, the *Experimental Long-Lead Forecast Bulletin* attracts contributions from an international research community. After testing with historical data, some of these new methods can be utilized in operational forecasting.

Like weather forecasts, these forecasts depend on global data collection and on the development of research results using a variety of computational models. Unlike weather forecasts, however, seasonal prediction depends critically on a historical meteorological database, usually referred to as climate data. Thus, seasonal climate prediction is the payoff of investment in atmospheric and oceanic research and demonstrates the value of maintaining a long-term climate record.

Whereas weather forecasts have their primary value in the short-term protection of life and property, and have a primary commercial user in the aviation transportation industry, the prediction of climate anomalies has demonstrated the value for economic decisions and regional societal planning. However, the use of long-lead, probabilistic seasonal outlooks for practical applications in water resources, agriculture, management of natural resources, human health, energy planning, business and commerce is not yet widely established.

The national Meteorological and Hydrological Services (NMHSs) are in the best position to develop the linkage between climatic forecasts and their applications for society and for commerce. This is a great opportunity for the NMHSs to bring together weather/water/climate forecast products for national and regional benefits. In addition to technical products, there is a need for additional development and an awareness of optimal decision-making using uncertain information.

In a sometimes hostile natural environment, climate information and predictions are a valuable resource for building sustainable development in developing countries; in the developed world this information is a resource for decision-making in a competitive market economy. Finally, the commercial sector of professional meteorologists are needed to use their expertise to develop a much larger customer base for applications of weather, water and climate forecast information than presently exists.

Acknowledgments

Much of the work reported here comes from the investigations of many scientists at the National Centers for Environmental Prediction and the Climate Prediction Center of the U.S. National Weather Service. In particular, I would like to acknowledge the contributions of H. Van den Dool, Chief of the Prediction Branch, and A. Leetmaa, leader of the Coupled Model Project. In addition, Tony Barnston, Michael Halpert, Vern Kousky, Arun Kumar, Richard Lehman, Richard Tinker and Steve Tracton

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contributed specific scientific expertise. Gail Lucas and Robert Churchill provided excellent support in the preparation of the figures.

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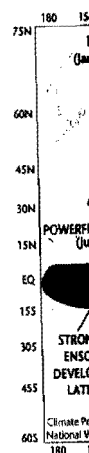


Figure 1



Figure 2

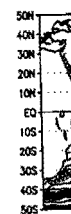
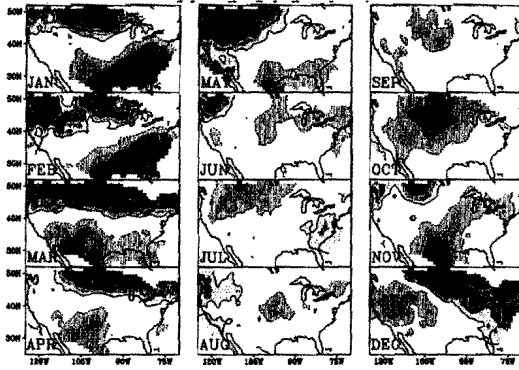


Figure 3

Composite Temperature Anomalies

Blues—below normal, Reds—above normal
contour interval 0.5 deg, solid—above normal, dashed—below normal
zero contour is not plotted



Composite Precipitation Anomalies

Blues—above normal, Reds—below normal
contour interval = 10 mm/month, solid—above normal, dashed—below normal
zero contour is not plotted

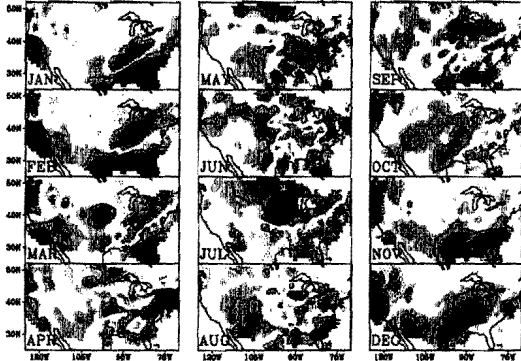


Figure 6 — Monthly composite for temperature (top) and precipitation (bottom) based on 0.5°C SST anomaly at the date line in the equatorial Pacific (Coupled Model Project, 1995).

850-mb Zonal Wind Anomaly 175W-140W

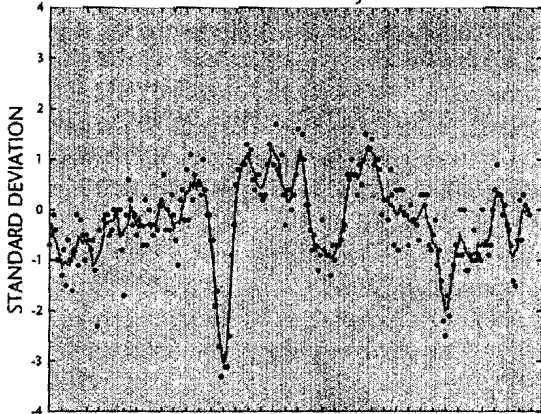


Figure 7 — Five-month running mean and individual monthly mean ("x"s) of the standardized 850-hPa zonal anomaly index in the latitude belt 5°N-5°S for longitude 175°W-140°W.

Climate Outlooks

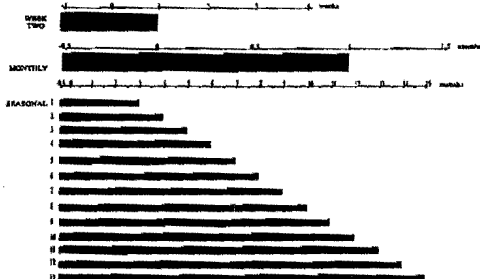
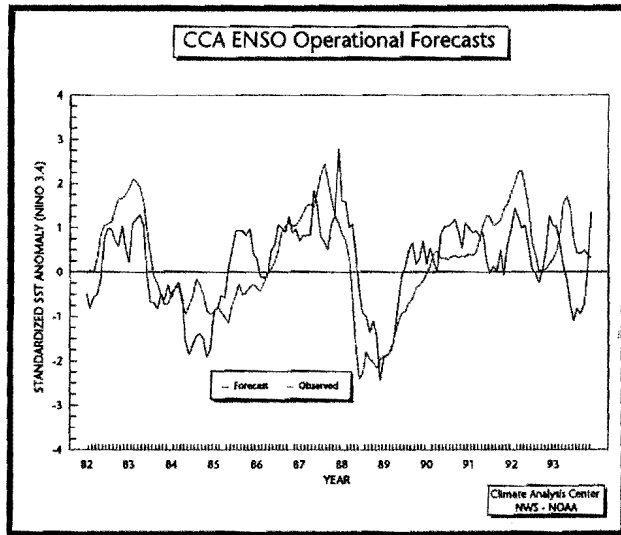


Figure 8 — Suite of climate prediction products at the NCEP/Climate Prediction Center.

CCA ENSO Operational Forecasts



C - Z ENSO Forecasts

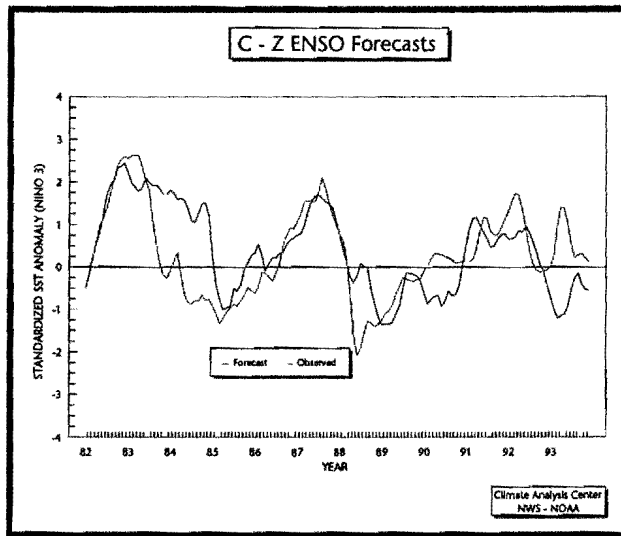


Figure 9 — ENSO/SST forecasts by the Climate Prediction Center (top) and by Zebiak and Cane (1987) (bottom).

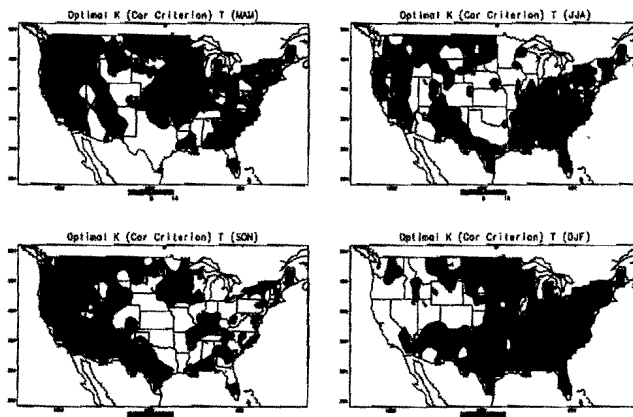


Figure 10 — Example of the optimum number of years (k) useful for predicting seasonal temperature anomalies a year in advance, based on 1931-1993 data. This analysis is used in the optimal climate normals (OCN) seasonal forecast method (Huang, Van den Dool and Barnston, 1994).

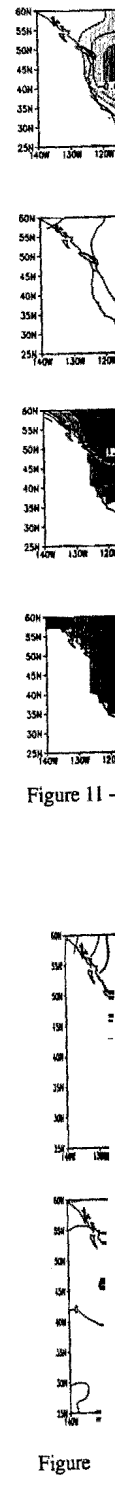


Figure 11 -
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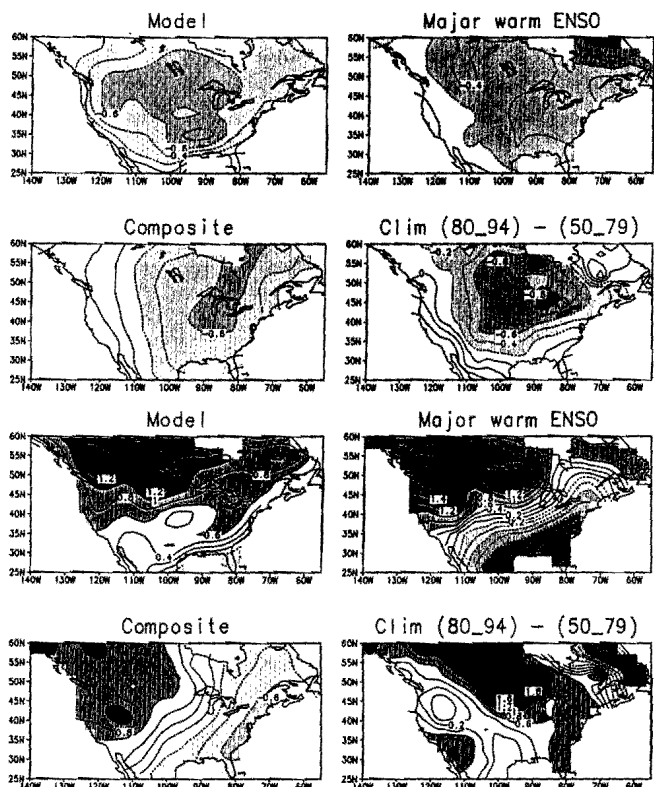


Figure 11 — Model results (specified SST) during October (top) and February (bottom) compared with observed ENSO composite conditions (Coupled Model Project, 1995).

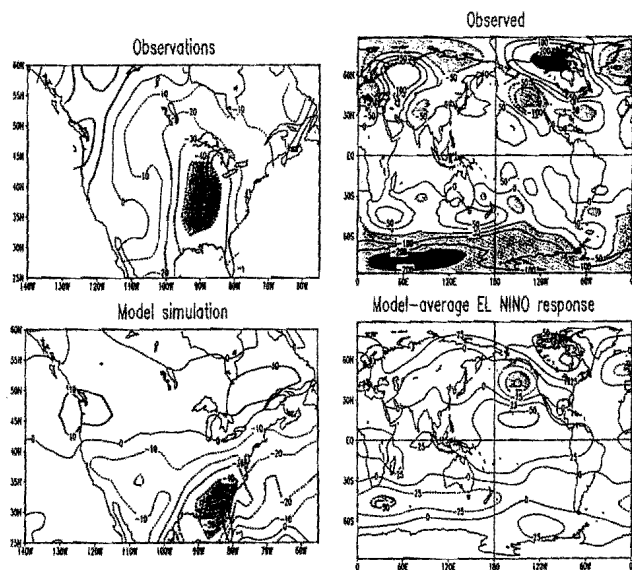


Figure 12 — Observed anomalous precipitation (top) and model results (with specified SST) (bottom) in mm/month during drought conditions in the spring/summer 1988 (Coupled Model Project, 1995).

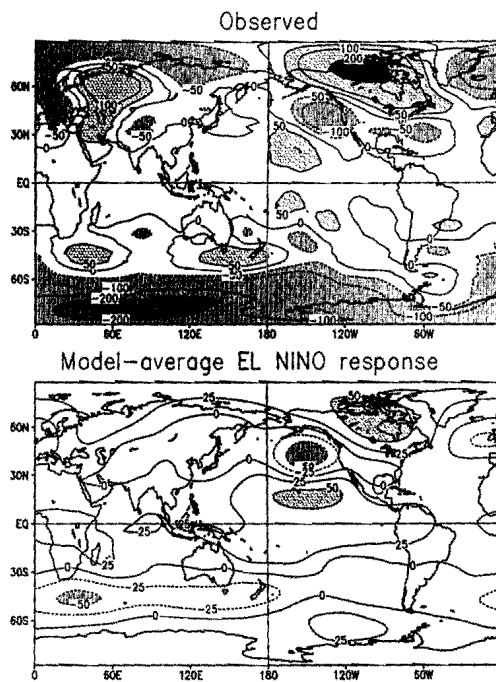


Figure 13 — Observed atmospheric geopotential 200-hPa height anomalies (top) and model results (with specified SST) during flood conditions in January 1995 (Coupled Model Project, 1995).

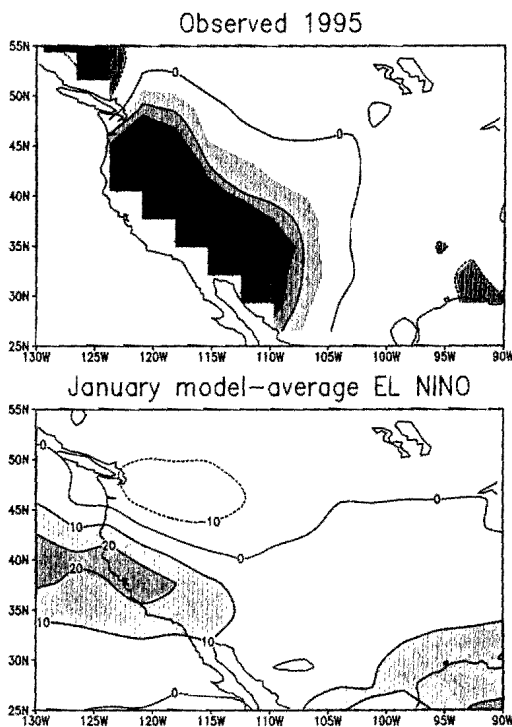
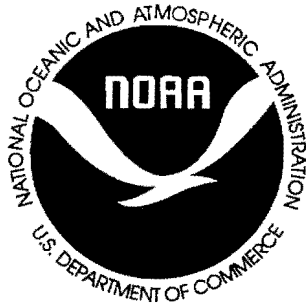


Figure 14 — Observed anomalous precipitation (top) and model results (with specified SST) (bottom) in mm/month during flood conditions in January 1995 in the western United States (Coupled Model Project, 1995).

CLIMATE OUTLOOK

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AUGUST 1995-OCTOBER 1996



National Weather Service
National Centers for Environmental Prediction
Climate Prediction Center

Climate Outlook August 1995-October 1996

The key below is used to interpret each of the color versions of the *Climate Outlook* products. In areas where confidence in predictive skill has been established, the probabilities of the above normal, near normal or below normal categories are increased accordingly above the climatological level of 1/3 for each category. These probabilities are contoured at 5% intervals using colors as depicted in the key below. In those areas where the skill of our present prediction tools is not sufficient, the default is climatological (white color). The probabilities of experiencing each of the three categories (above normal, near normal or below normal) remain equally likely (1/3) in the white areas as attached maps.

| Precip | Temp | Probability anomaly as shown on map | Probability of occurrence for each class | | | Most likely category |
|-----------------------------|---------------------------|-------------------------------------|--|------------|------------|----------------------|
| | | | A | N | B | |
| [Color swatches for Precip] | [Color swatches for Temp] | 15%-20% | 48.3-53.3% | 33.3% | 13.3-18.3% | "Above" |
| | | 10%-15% | 43.3-48.3% | 33.3% | 18.3-23.3% | "Above" |
| | | 5%-10% | 38.3-43.3% | 33.3% | 23.3-28.3% | "Above" |
| | | 0%-5% | 33.3-38.3% | 33.3% | 28.3-33.3% | "Above" |
| [Color swatches for Precip] | [Color swatches for Temp] | 0%-5% | 30.8-33.3% | 33.3-38.3% | 30.8-33.3% | "Near Normal" |
| | | 5%-10% | 28.3-30.8% | 38.3-43.3% | 28.3-30.8% | "Near Normal" |
| | | 0%-5% | 28.3-33.3% | 33.3% | 33.3-38.3% | "Below" |
| | | 5%-10% | 23.3-28.3% | 33.3% | 38.3-43.3% | "Below" |
| [Color swatches for Precip] | [Color swatches for Temp] | 10%-15% | 18.3-23.3% | 33.3% | 43.3-48.3% | "Below" |
| | | 0% | 33.3% | 33.3% | 33.3% | "Climatodgy" |

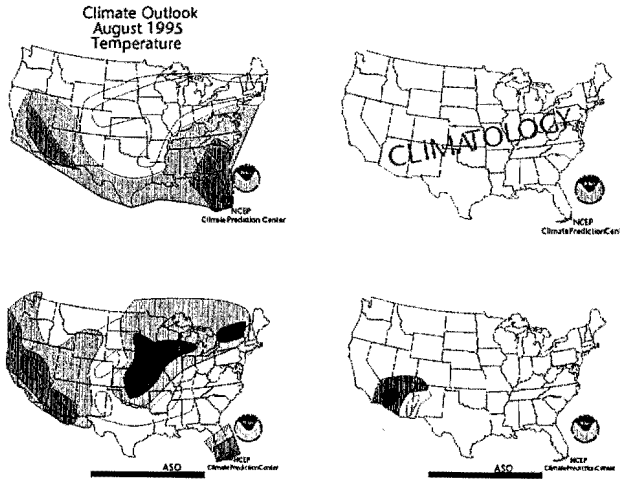


Figure 15 — (a) The *Climate Outlook* for August 1995; (b) legend; and (c) the August and first season (August, September and October) outlook for 1995.

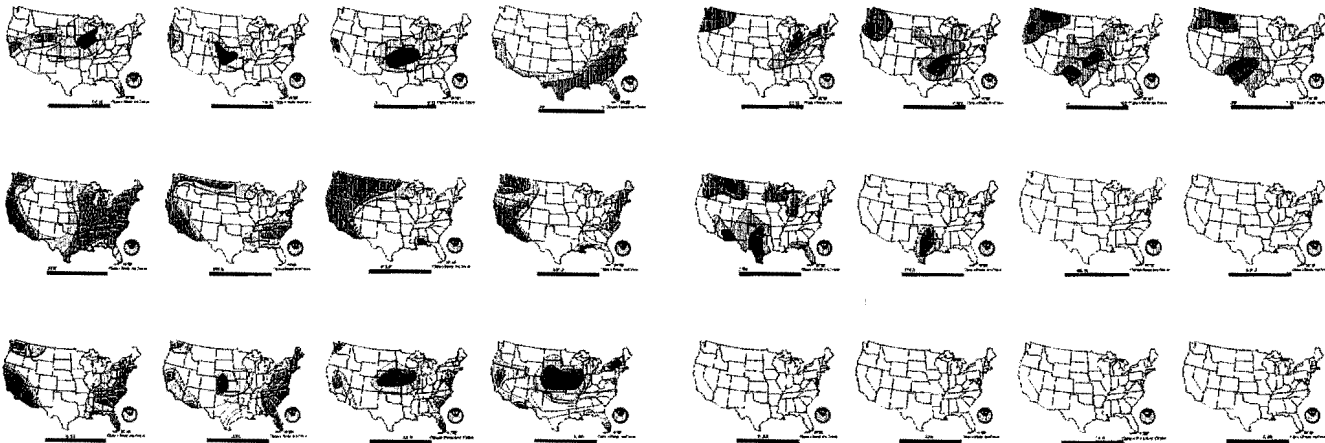


Figure 16 — The *Climate Outlook* for September, October and November 1995 — August, September and October 1996: (a) seasonal temperature; and (b) seasonal precipitation.

Fig

Figure 18 -

Figure 1

CPC Server Usage

ftp://ftp.ncep.noaa.gov Sat Mar 18 11:41:46 EST 1995, server started Oct 16 1994

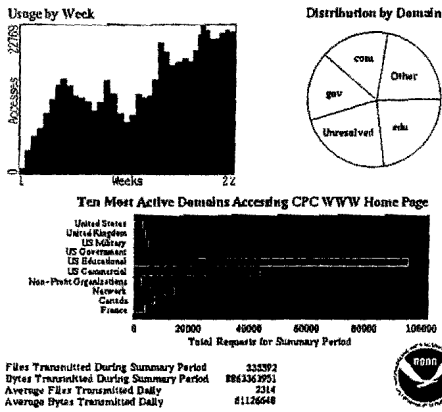


Figure 17 — User access on the CPC Internet Home Page.

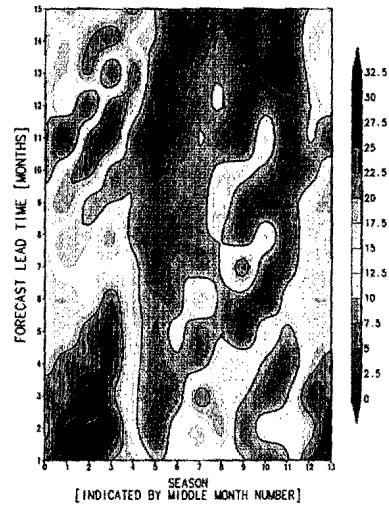


Figure 20 — Historical skill of the canonical correlation analysis (CCA) mean temperature forecast for each season (three months) for northern Europe.

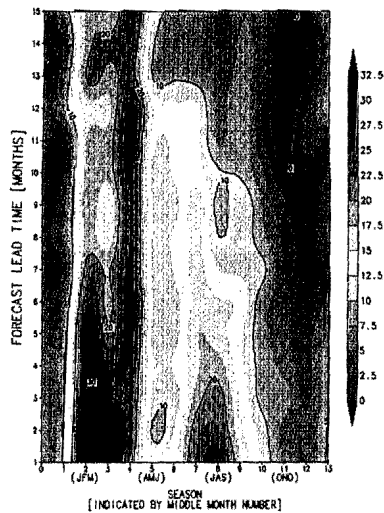


Figure 18 — Historical skill of the canonical correlation analysis (CCA) mean temperature forecast for each season (three months) for the continental United States.

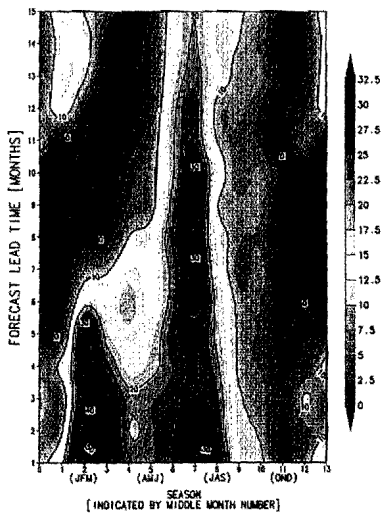
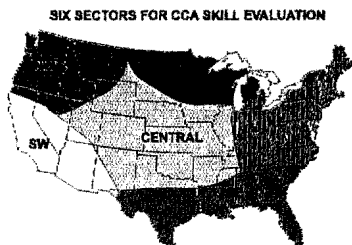


Figure 19 — Depiction of United States regions used for CCA skill evaluation (top) and historical skill of the canonical correlation analysis (CCA) mean temperature forecast for each season (three months) for the south-eastern United States.

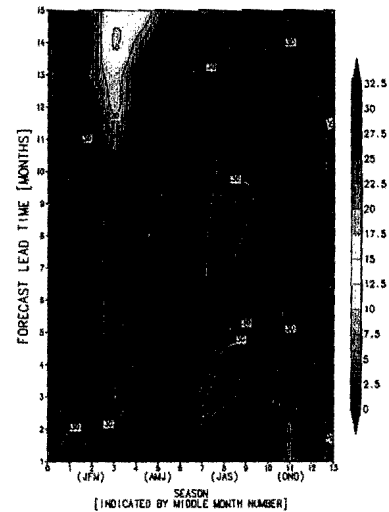


Figure 21 — Historical skill of the canonical correlation analysis (CCA) mean temperature forecast for each season (three months) for Hawaii.


NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE
 EXPERIMENTAL LONG-LEAD
FORECAST BULLETIN

JUNE 1995
Vol. 4, No. 2

National Weather Service
National Centers for Environmental Prediction
Climate Prediction Center

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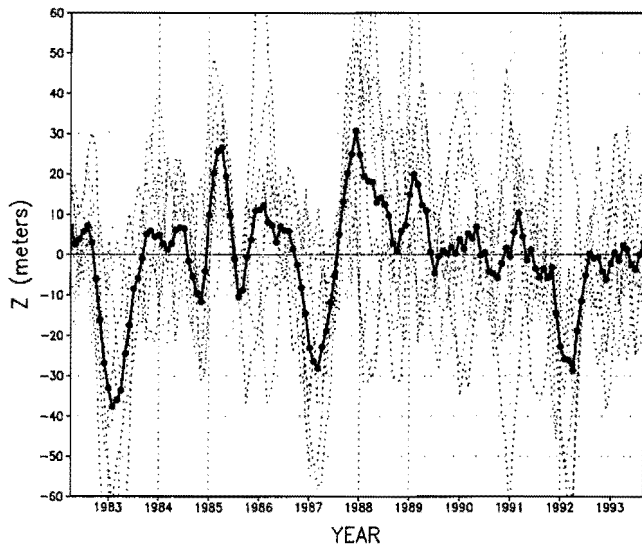


Figure 23 — Five-month running mean of the 200-hPa height anomaly averaged between 30°N and 60°N for nine runs of a coupled model and the ensemble mean (dark line).

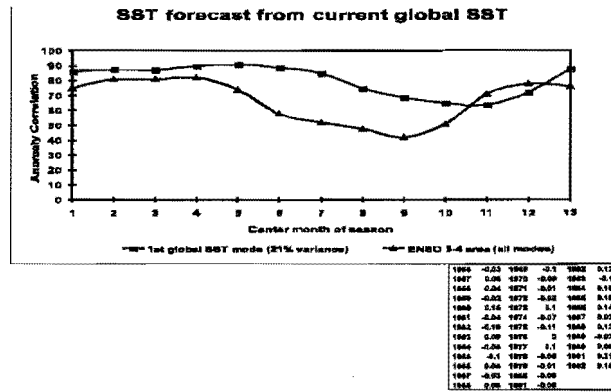


Figure 24 — Two-season lead forecast of SST in the tropical Pacific from a constructed analogue.

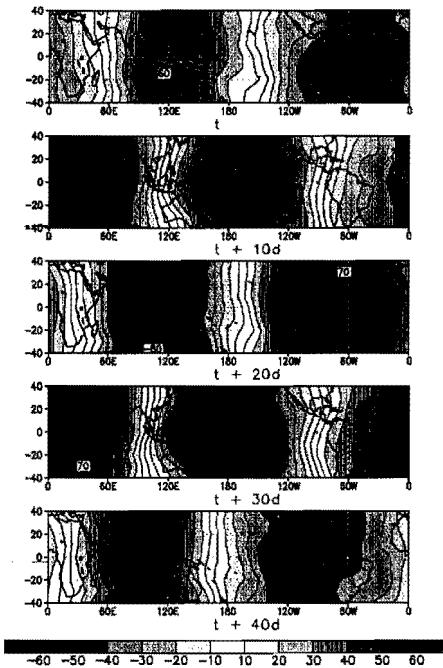


Figure 25 — Sequence of the lowest mode of velocity potential for the M-J oscillation over a 40-day period (Kousky and Kayano, 1994).

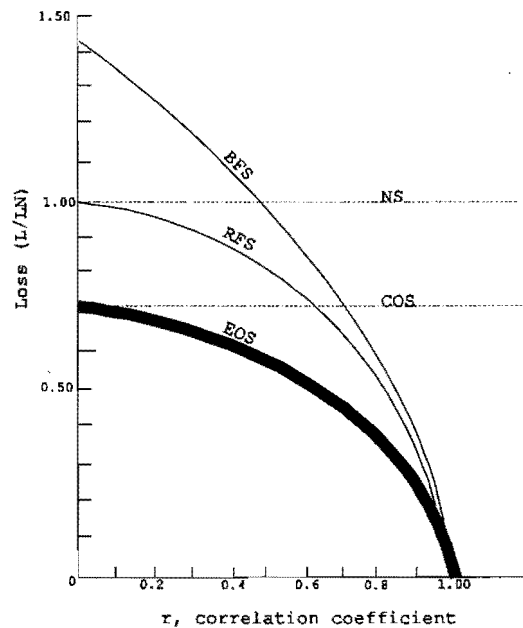


Figure 26 — The comparative value/loss of historical climatological information and a climatological forecast (Gandin, Murphy and Zhukovsky, 1994). Losses are minimized for an economically-optimum strategy (EOS).

International World Climate Programme

(WMO, UNEP, ICSU, FAO, UNESCO/IOC, UNDP)

The Climate Agenda

Four Thrusts:

1. Climate Services for sustainable development.
2. New frontiers in climate science and predication.
3. Dedicated observations of the climate system.
4. Studies of climate impact assessments and response strategies to reduce vulnerability.

Figure 27 — The four major thrusts of the new interagency WCP.

World Climate Applications and Services Programme (WCASP)

Climate Information and Prediction Services (CLIPS) Project

Objectives

- provide an international framework
- strengthen a global network of regional/national climate centers
- demonstrate the value of climate information and services
- encourage development of operational climate predictions

Figure 28 — Objectives of the Climate Information and Prediction Services (CLIPS) programme.