Report of the JCESS-CLIVAR Workshop on Decadal Climate Variability

Vikram M. Mehta
NASA-Univ. of Maryland Joint Center for Earth System Science
Department of Meteorology
University of Maryland
College Park, Maryland 20742, U.S.A.
mehta@atmos.umd.edu

FINAL
4 December 1996

Foreword

The idea of organizing this Workshop grew out of a general feeling in the decadal climate variability community that there was a need to get together to discuss recent results, exchange ideas, and formulate a plan of research in decadal climate variability, its predictability, and applications. Participation in the Workshop was limited due to logistical constraints and I apologize to the many interested scientists whose requests for participation had to be declined. The interest of these scientists to participate in the Workshop and the enthusiasm of those who participated is symptomatic of the need for regular meetings on this subject. The presentations and discussions in the Workshop are summarized in this Report. A program of research in decadal climate variability, its predictability, and applications was discussed in the Workshop. This Report also contains recommendations for such a program to national and international funding agencies, and the International CLIVAR program. All participants had an opportunity to comment on the draft Report and their comments are included in the final version.

My work of organizing the Workshop and preparing its Report was made considerably easier by help and advice from many participants, especially Tony Busalacchi, Allyn Clarke, Mike Coughlan, Tom Delworth, Clara Deser, Bob Hudson, Bill Lau, Mojib Latif, Syd Levitus, Mike MacCracken, Claudia Nierenberg, Scott Power, Ellen Rice, Norm Rosenberg, Ed Sarachik, Max Suarez, Kevin Trenberth, and Andreas Villwock. I am grateful to Ken Bergman, Mike Coughlan, and David Goodrich for the financial support provided by NASA, the International CLIVAR program, and NOAA, respectively. I am also grateful to Peggy Small, Charlene Mann, and Rick Bosley for making logistical arrangements, and to Peggy Small for preparing this Report.

Vikram M. Mehta
Chairman, JCESS Council

Summary

The JCESS-CLIVAR Workshop was organized under the auspices of the NASA-Univ. of Maryland Joint Center for Earth System Science (JCESS) and the WCRP CLImate VARiability and predictability program (CLIVAR) to bring together researchers to assess the state of the science of natural decadal climate variability and its societal impacts, and to formulate a program of research in various aspects of natural decadal climate variability, its predictability, and applications of the predicted information.

The results of the preliminary analyses of observations and model experiments presented in the Workshop, and previously published literature on this subject were discussed by the Workshop participants.

Workshop conclusions

- The relative shortness and quality of the instrument-measured climate record only allows us to quantify characteristics of climate variability at time scales upto 10-20 years.

- There are several phenomena exhibiting climate variability at decadal time scales, some of which appear to have distinct time scales and some appear to have "red noise" characteristics. The following phenomena appear to be the most promising for understanding and developing predictive skill.

  1. The El Nino-Southern Oscillation (ENSO),
  2. The tropical Atlantic SST and the associated climate variability over the tropical Atlantic, the Americas, and Africa,
  3. Wind-driven ocean circulations (North Atlantic and North Pacific) and their interaction with the atmosphere,
  4. The North Atlantic thermohaline circulation and its interaction with the atmosphere.

- There is some predictability inherent in the persistence attached to the slow time scales of some components of the climate system, in particular, the oceans and sea ice. However, To enhance understanding and predictive skill, it is very important to determine whether these promising phenomena exhibit distinct decadal oscillation time scales.

- An improved understanding of natural decadal variability is needed to distinguish anthropogenic climate change from natural variations.

- Several global coupled ocean-atmosphere models simulate various aspects of some of the observed decadal time scale phenomena.

- Three of the decadal time scale phenomena (the North Atlantic thermohaline circulation variability, the tropical Atlantic SST variability, and the tropical Pacific SST variability) appear to be potentially predictable at lead times of several years because they exhibited dominant oscillation periods during the analysis period. Predictability of the thermohaline circulation variability was studied using a global coupled ocean-atmosphere model and predictability of the tropical SSTs was studied using statistical models fitted to SST observations.

- Many of the global climate models in current use do not adequately represent the processes likely to be important in decadal climate variability, and its interactions with interannual variability and anthropogenic climate change.

- Hurricane damage potential in the U.S. and the Caribbean countries has exhibited decadal-multidecadal variability.

- The world food and water supplies may be vulnerable to decadal time scale climate variations.

Workshop recommendations

Based on the agreed-upon conclusions, it was decided to make the following initial recommendations to national and international funding agencies, and the International CLIVAR program.

Recommendation 1:

In view of the possible predictability of the decadal climate variability phenomena and their impacts on the society, it was the consensus opinion of the participants that a research and applications program should be organized to reconstruct the past decadal variability from the instrument-measured and paleoclimate data; to understand mechanisms of decadal climate variability; to assess its potential predictability; to develop models that realize its potential predictability; and to apply the predicted information for societal benefits. This program should be a major component of the DecCen component of International CLIVAR program.

Recommendation 2:

This program should focus on the decadal variability of

1. the ENSO,
2. the tropical Atlantic SST and the associated climate variability over the tropical Atlantic, the Americas, and Africa,
3. wind-driven ocean circulations (North Atlantic and North Pacific) and their interaction with the atmosphere,
4. the North Atlantic thermohaline circulation and its interaction with the atmosphere.

The first two phenomena should be accorded the highest priority since they appear to be the most promising for understanding and prediction.

Recommendation 3:

Past decadal time scale variability should be reconstructed using the available instrument-measured and paleoclimate data. For understanding and prediction, it is important to determine whether the above-mentioned observed phenomena occur at preferred decadal oscillation time scales.

Recommendation 4:

Comprehensive global climate models should be developed that adequately represent the processes likely to be important in decadal climate variability, and its interaction with interannual variability and anthropogenic climate change. Such models should be free from artificial intervention in the evolution and variability of the model climate.

Recommendation 5:

Predictability and applications studies should be integral components of the program.

Recommendation 6:

The following program elements are proposed to achieve these goals.

1. Organization of instrument-measured and paleoclimate time series
2. Development of dynamical models suitable for the study of decadal climate variability and its predictability
3. Diagnostic and model-evaluation studies with the instrument-measured and paleoclimate data, and dynamical models
4. Predictability studies using statistical and dynamical models
5. Applications feasibility studies
6. Long-term monitoring of the decadal variability phenomena and observing system simulation studies

Recommendation 7:

The program should be implemented via the following near-term action items.

1. Locate, collect, quality-check, and document instrument-measured time series of climate quantities; and create interconnected Internet Web sites pointing to such data.
2. Locate, collect, quality-check, and document paleoclimate data, reconstruct equivalent surface temperature and precipitation from the paleoclimate data; and create interconnected Internet Web sites pointing to such data.
3. Develop comprehensive, very high resolution, global coupled ocean-atmosphere-land models without artificial interventions.
4. Test and evaluate these models rigorously for their ability to simulate the annual cycle, the ENSO, and the various decadal climate variability phenomena.

5. Conduct carefully designed model experiments to address the science questions relating to the various instrument-measured and paleoclimate data and to identify "targets" for modeling and prediction studies.
6. Conduct studies of decadal predictability with statistical and dynamical models to estimate forecast skill and lead time for the various decadal variability phenomena.
7. Make all model output widely available for analysis.
8. Form a panel consisting of decadal variability researchers, applications experts, and government officials to develop an integrated applications studies program and to monitor its progress.
9. Set up an observing program component for long term monitoring and specialized observations of the decadal climate variability phenomena.
10. Organize Workshops every two years to assess the progress of the program.

Table of contents

1. Introduction

The survival of life on the Earth depends on water. Human, plant, and animal life are stressed when necessary water is not available. While some living systems can cope with water stress for a few days or months, most are severely stressed by years or decades of reduced water supply.

It is well-known that climate variability causes variability in water supply over subseasonal and longer time scales. Analyses of rainfall records indicate that droughts lasting many years occur quasi-regularly in the United States, India, China, Brazil, and western and southern Africa. The "Dust Bowl" phenomenon in the 1930s was an example of decadal time scale droughts in the United States. The El Nino-Southern Oscillation phenomenon, its associated global climatic perturbations, tropical cyclone activity in the Atlantic, and extra-tropical storms also exhibit decadal (10-20 years period) variability. If the natural fluctuations in precipitation; the resultant fluctuations in water supply; and fluctuations in other climate variables such as surface air temperature, surface air humidity, and soil moisture at decadal time scales can be predicted some years in advance, the effects of these fluctuations on agriculture, water resources, public health, and other societal activities may be mitigated/exploited to benefit society.

In addition to variations in water supply as a result of natural climate variations, global and regional climates can also be perturbed by anthropogenic influences at decadal and longer time scales. Not only can natural decadal variability interfere in the detection and quantification of anthropogenic climate change, but natural variability is also modified by anthropogenic climate change. For these reasons, it is very important to identify the spatio-temporal characteristics of natural decadal climate variability phenomena, the physical processes responsible for them, the important issues in improving the understanding and the ability to model them, and determine the extent to which these phenomena may be predictable.

During the last few years the international climate research community has started to investigate decadal climate variability and its possible mechanisms. This Workshop brought together researchers to assess the state of the science of natural decadal climate variability and its societal impacts, and to formulate a program of research in various aspects of decadal climate variability, its predictability, and applications of the predicted information. This Workshop was also a contribution to the CLImate VARiability and predictability program (CLIVAR) of the World Climate Research Program (WCRP), whose scientific objectives encompass seasonal to centennial time scales.

Because the main topic of presentations and discussions in the Workshop was natural decadal climate variability, the possible interaction between natural decadal variability and anthropogenic climate change/variability was not addressed. It is very important, however, to understand this interaction for understanding and prediction of both classes of phenomena. Therefore, observation and modeling studies of this interaction are included in the Workshop recommendations. Details of observing program were not discussed in the Workshop but, in view of the importance of such a program, it is included in the Workshop recommendations.

This Report contains summaries of the various Workshop sessions, major conclusions drawn from the presentations and discussions, and recommendations for a research program. The summary of the Societal Impacts session is more detailed than the summaries of the other sessions to develop a greater awareness among climate scientists of societal impacts of climate variability. The author names are embedded within or mentioned at the end of the summary of each presentation.

Extended abstracts of presentations are appended to the Report.

2. Summary of presentations

2.1 Observations of decadal climate variability

2.1.1 Data coverage and quality

Analyses of a variety of instrument-measured data were presented in the Workshop. The main climate quantities analyzed were ocean temperatures from the surface to 400 meter depth in the North Atlantic and North Pacific Oceans; atmospheric pressure over the North Atlantic and North Pacific Oceans; rainfall over North America, Africa, northeast Brazil, and Australia; and wind stress on the tropical Pacific Ocean. Except for the sub-surface ocean temperatures which are available for only the recent 30-40 years, the other quantities are available for 60 to 140 years. Analyses of other indicators of regional climate, such as the tropical Atlantic cyclone activity, were also presented.

The data quality was found to be adequate to analyze decadal climate variability in the period since the Second World War. Serious concern was expressed about trends due to changes in measurement techniques in sea surface temperature (SST) data between the 1850s and the 1940s. Because more than one independently measured quantity, e.g., SST and sea level pressure (SLP), shows similar decadal variations over the North Atlantic and Pacific, the tropical Atlantic and Pacific, and Australia in the period before the Second World War, it appears that the data quality may be adequate for studies of natural decadal variability over much of the available instrument-measured record. There should, however, be rigorous attempts to check data quality, especially their quantitative accuracy.

2.1.2 Observations of decadal climate variability at the mid-high latitudes

Decadal variability in SST, upper-ocean thermal structure, and SLP have been found in the North Atlantic and North Pacific. Compared to variability in other ocean basins, decadal variability of the North Atlantic SST appears to be distinct (**Kushnir**). In the North Atlantic, the upper-ocean thermal structures in the subtropical gyre and the subpolar gyre during 1966-1990 appear to oscillate with opposite phases (**Levitus**). The oscillations in the upper-ocean thermal structure in the western portion of the North Atlantic subtropical gyre were shown to be linked to variations in the North Atlantic Oscillation, a north-south see-saw in SLP (**Molinari**). Although the power spectrum of the North Atlantic SST variability is "red" and that of SLP variability is "white", the coherence between the two exhibits a spectral peak at decadal time scales (**Kushnir**). Superimposed on the decadal variability of the North Atlantic upper-ocean thermal structure, there appears to be a cooling trend in the subpolar gyre and a warming trend in the subtropical gyre. An analysis of relatively short (1970-1991) records of upper-ocean thermal structure in the central North Pacific shows downward and southward movement of thermal anomalies from the ocean surface into the main thermocline. Decadal thermal variations appear to be more prominent within the main thermocline than at the sea surface in the North Atlantic (**Molinari**) and the North Pacific (**Deser**), indicating that the thermocline may be a more useful region for monitoring decadal time scale climate variations than the ocean surface.

One of the major roles of the ocean in the global climate system is to transport heat poleward, thereby moderating the climate of the mid-high latitude regions. Variations in meridional heat transport can give rise to variations in the mid-high latitude surface climate. There have been several estimates of meridional heat transport by the Atlantic Ocean circulation. A systematic study of the sources of error in meridional heat transport demonstrated that inhomogeneities in the surface fluxes preclude meaningful estimates of the long term meridional heat transport and its variability on decadal time scales (**Gulev**).

Deep-water formation in the oceans partially due to cooling of the surface water at high latitudes occurs over small spatial scales. The problem of estimating variability of deep-water formation is especially difficult in the data-sparse southern oceans where deep-water formation may occur over horizontal scales less than 10 km along the continental shelf. The areal extent and thickness of sea ice control the sea-air heat flux and are themselves influenced by upward heat transport from the deep ocean resulting in multi-year polynya events (**Gordon**).

2.1.3 Observations of decadal climate variability at the tropical latitudes

Decadal variability of the tropical climate has been examined mainly as represented in long records of surface temperatures (land and sea) and rainfall. Long time series of proxy quantities such as coral records and the tropical Atlantic cyclone activity index have also been analyzed.

There were several presentations on decadal-multidecadal variability of the ENSO phenomenon. Low-frequency variations in the Nino3 SST (average SST over the eastern and central equatorial Pacific, an index of the ENSO phenomenon) were found to be filter-dependent, but a comparison of the Nino3 SST variability with Bombay (India) SLP variability during the last 100 years or so was found to provide a consistent picture of multidecadal variability of the ENSO (**Rasmusson et al.**). Analyses of instrument-measured SST data over the tropical Pacific since the early 1930s show that the spatial structures of decadal-multidecadal variability extends from the northeastern tropical Pacific to the western equatorial Pacific and are thus substantially different from the structures of the ENSO SST anomalies which are largely confined to the eastern equatorial Pacific. SST anomalies at decadal-multidecadal time scales appear to travel from the northeastern and occasionally southeastern extra-tropical Pacific to the western equatorial Pacific, and appear to grow in areal extent and amplitude in the tropical Pacific. Wind stress anomalies were found to be physically consistent with the decadal-multidecadal SST anomalies (**Mehta**). Another analysis of instrument-measured SST data showed that interannual variability is more concentrated in tropical latitudes, whereas decadal variability contains a larger extratropical component. In addition, the spatial pattern of decadal variability has a broader meridional extent. The autocorrelation of the North Pacific SSTs was substantially greater than that of the tropical SSTs, demonstrating that the more pronounced decadal variability is in the extra-tropics (**Zhang and Wallace**).

Possible causes of the recent anomalously warm eastern equatorial Pacific and current global-average temperatures were the topic of two presentations. It was pointed out that the recent persistent warm anomalies in the eastern Pacific may not be as unusual as claimed in other studies in which Auto Regressive-Moving Average (ARMA) models were used. Two different methods were used to estimate the probability for such a long warm event to occur. Both the Markov chain and Poisson process approaches yield higher probabilities for the occurrence of persistent anomalies relative to the ARMA approach (**Rajagopalan and Cane**). Can the warming be due to anthropogenic climate change? It was shown that recent modification of planetary waves over the Northern Hemisphere by the ENSO, the Pacific-North American pattern (PNA), and the North Atlantic Oscillation (NAO) variability appear to be such that 47% of the recent warming in the December-March Northern Hemisphere temperature is explained by these phenomena. This study pointed out the importance of how these natural phenomena (ENSO, PNA, NAO) may be altered by anthropogenic climate change (**Trenberth**).

The tropical Atlantic SST varies at decadal-multidecadal time scales. The dominant pattern has SST anomalies of opposite polarities to the north and south of the equator with the maximum amplitude at approximately 15˚ N and 15˚ S. The dominant time scale of oscillation is approximately 12-13 years. There is SST variability at 30-40 year time scale also. The tropical Atlantic SST variability during the 20th century is associated with variability in rainfall over the north Nordeste Brazil and western Africa, and with cyclone activity in the tropical Atlantic region (**Mehta**). Some of the multidecadal variability of rainfall over Africa, particularly over central Sahel, may be associated with land surface processes and not with SST variability in the adjacent ocean basins (**Grist and Nicholson**).

Another example of association between SST variability and climate variability over adjacent continents was the decadal variability of Australian climate. Gridded rainfall and surface air temperature data for the period 1910-1992 were analyzed and it was shown that there is physically-consistent decadal variability in both quantities. The rainfall variability is also consistent with variations in the flow of the major Australian river, the Murray. The decadal variability of Australian climate appears to be correlated with SST variability in the Indian and Pacific Oceans (**Power et al.**).

2.1.4 Analyses of proxy data

As mentioned earlier, at least 100-200 years long time series of a climate quantity would be required to estimate statistics of decadal climate variability. Because most instrument-measured climate time series are less than 100 years long, climate indicators such as tree rings and corals have been used to generate much longer time series of climate quantities. Such proxy data are available only in some regions and it is difficult to retrieve primary climate quantities such as rainfall and temperature from these data. Such data, however, can be qualitative indicators of climate variability. Several reports from analyses of tree ring and coral time series were presented in the Workshop.

Wavelet analysis of an approximately 350 years long coral record from the Galapagos Island in the eastern equatorial Pacific Ocean revealed intermittence of the ENSO and decadal-multidecadal variabilities. Variability at time scales longer than 10-15 years is highly coherent between the coral record and reconstructed SSTs during the period 1868-1993 (**Meyers and O'Brien**). Using selected long (1700-1980), precisely-dated, gridded tree-ring records from the U.S., it was shown that the dominant oscillation periods over the midwestern and western U.S. correspond to the droughts in the 1930s, 1950s, and 1970s. It was suggested that the decadal-multidecadal variability over the midwestern U.S., indicated by the tree-ring results, may be associated with variability of the Pacific SSTs (**Cook**).

2.1.5 External influences on the climate system at decadal-multidecadal time scales

There are two possible external influences on the climate system at decadal-multidecadal time scales; variability in solar radiation and aerosol loading of the atmosphere due to volcanic eruptions. Decadal time scale changes in climate forcing by changing solar radiation were compared with the observed surface temperature changes. It was suggested that surface temperatures may be covarying with the 11-year solar irradiance cycle (**Lean**). Aerosol loading was found to result in 0.1°C cooling in global-average surface temperature approximately two years after a major volcanic eruption. This result was confirmed by experiments with an atmosphere GCM. It was suggested that the cumulative effect of several successive eruptions may influence climate at decadal time scales (**Free and Robock**).

2.2 Modeling of decadal climate variability

Analyses of decadal variability in three types of models were described; coupled ocean-atmosphere general circulation models (GCMs), hybrid models based on coupled GCMs, and idealized ocean and ocean-sea ice models.

Interaction between wind-driven ocean circulation and the atmosphere appears to generate decadal variability in the North Pacific climate of the ECHO (Max-Planck Institute) and the GFDL coupled GCMs. The spatial pattern of the model-generated SST variability resembles the observed Pacific SST variability described in the previous section. In the ECHO GCM, the variability has a period of approximately 18 years (**Latif, Barnett and Xu**), and is associated with wave propagation and ocean adjustment time scales. The estimated spectrum of the variability in the GFDL GCM is predominantly "red" but does contain coherent features traveling along the subtropical Pacific gyre at decadal time scales (**Delworth**). The spatial pattern of the North Pacific SST variability in the GFDL atmosphere GCM coupled to a mixed-layer ocean model also resembles the observed SST pattern (**Delworth**). A hybrid coupled model consisting of the ocean component of the ECHO model coupled to a statistical atmosphere reproduces the North Pacific decadal variability found in the ECHO model (**Barnett and Xu**). It was also suggested that interaction between the North Atlantic wind-driven circulation and the atmosphere may also cause decadal variability. Results from the ECHO model were compared to the observed North Atlantic SST variability (**Latif**).

It is well-known that thermohaline ocean circulation in coupled ocean-atmosphere and ocean-only models oscillates at several decades to several thousand years time scales. An example of multidecadal variability in the North Atlantic of a coupled model due to interaction between the thermohaline circulation and the atmosphere was presented (**Latif**). The thermohaline circulation can also be modulated by, among other processes, anomalous freshwater flux in the form of sea ice. Anomalous sea ice amounts can also change the air-sea heat flux and the amount of net radiation at the surface. The sensitivity of decadal variability in the NCAR coupled GCMs to fractional sea ice threshold was described. A threshold of 0.5 resulted in variability at 30 years time scale; this changed to 15 years when a threshold of 0.75 was prescribed (**Meehl**). In a sensitivity study with an ocean GCM coupled to a thermodynamic/dynamic sea ice model, the thermohaline circulation was significantly modified by doubling sea ice export from the Arctic into the North Atlantic (**Hakkinen**).

An instability of thermal-only meridional ocean circulation to tropical forcing was described. When, for instance, a warm SST anomaly develops in the tropical Pacific, a cold SST anomaly might be generated in the midlatitudes via atmospheric teleconnections. The cold surface water in the midlatitude Pacific might then be subducted, flow southward, and eventually be upwelled at the equator, thereby causing a cold SST anomaly at the equator. This multidecadal oscillation might then modulate the ENSO phenomenon (**Gu and Philander**).

Ocean models are known to generate interannual and longer time scale variability entirely due to internal dynamics. An example of such internal ocean variability was described in which currents normal to a weakly stratified coast resulted in a boundary wave propagating around the perimeter of the ocean basin on decadal time scales. This mode was found to have some dependence on basin topography, and is less likely to occur in a basin with bowl-shaped topography than in a basin with a flat bottom (**Winton**).

2.3 Predictability of decadal climate variability

The importance and prospects for decadal climate prediction were discussed, and the predictability of some of the decadal variability phenomena described in the previous two sections was explored with dynamical and statistical models.

An ensemble of prediction experiments were carried out with the GFDL coupled GCMs to assess the predictability of 40-70 year variations in the North Atlantic thermohaline circulation. Initial conditions of the model atmosphere were different in each member of the ensemble. The same initial conditions of the model ocean were prescribed in all members. Substantial levels of predictability, five to ten years in advance, were found for the EOF time series of dynamic height anomalies. These results highlight the potentially greater predictability of integrated quantities at decadal-multidecadal time scales (**Bryan and Griffies**).

The predictability of the tropical Atlantic and tropical Pacific SST variability at decadal-multidecadal time scales was explored with statistical models. Autoregressive (AR) models of various orders were fitted to the tropical Atlantic and tropical Pacific SST EOF time series. The EOF time series were filtered using the Singular Spectrum Analysis to retain only decadal-multidecadal variability. Using the past data to initialize the AR models selected by the Akaike Information Criterion, "future" SST anomalies were predicted and compared with independent data. Substantially accurate predictions of the amplitude and phase of the tropical Atlantic and tropical Pacific SST variability were found ten years in advance (**Mehta**).

In both the above cases, the long lead time predictability results from the apparent dominant oscillation periods and not due to long persistence times of anomalies. In the case of statistical prediction of the tropical Atlantic and Pacific decadal SST anomalies, the results are based on the premise that the past and future characteristics of the decadal variability will be similar. The relative shortness of the instrument-measured SST time series in the tropical Atlantic and Pacific Oceans, however, does not lead to high confidence that this premise will be valid in the future.

2.4 Societal impacts

Climate impacts are measured by the physical effects of the climate variability (in particular by the intensity of precipitation, winds, and temperature at the land surface) and by the vulnerability of the system of interest to these physical fluctuations. The concept of vulnerability is complex and is still a topic of fundamental research. Vulnerability varies from system to system but we can use our intuition in applying the concept to societies as a whole: vulnerability decreases with increases of economic development and increases with the time scale of climate fluctuations. Thus a poor country such as Peru is vulnerable to seasonal-to-interannual climate fluctuations and surviving an adverse climatic year has a higher priority than thinking about long runs of adverse climatic conditions. The U.S., however, is less vulnerable to a single adverse year, but even with the world's richest economy, is more vulnerable to a decade of adverse climatic conditions. A decade of below-normal rainfall in the major agricultural areas in the U.S. would cause economic, social, and political chaos not only in the U.S. but also in many other countries. While seasonal-to-interannual fluctuations are still of interest and can be exploited if predicted, it is not until the global economy is threatened by decadal climate fluctuations that the true importance of decadal climate predictions becomes apparent. The prospects for predicting decadal variability depend on understanding the mechanisms for the variations. Among the possible mechanisms, coupled ocean-atmosphere modes offer the best prospects for prediction (**Sarachik**).

2.4.1 An approach to applications of climate forecasts

The term "climate impacts" is normally used to refer to the repercussions of climatic events, usually those experienced by people, ecosystems, and the environment. Now that advanced climate analyses and computer-based climate modeling are beginning to offer predictive insights into the likelihood of seasonal-to-interannual precipitation and temperature patterns for some parts of the world, the potential exists to both mitigate harmful impacts of climate variation and to exploit the benefits. Using examples of early attempts to base actions on climate information, **Nierenberg** tried to convey a different perspective from those held by the physical science community. Rather than looking at the magnitude of severe weather during a climate season as a proxy for the impacts on society, she indicated that there is social science research which analyzes the nature of vulnerability to climate variation. When considering the possibility of adjusting existing decision-making, in water management or agricultural planning specifically, climate information can indeed be a useful input if considered within the full context of factors affecting outcomes. For example, a climate forecast may indicate a season when conditions would be best for crops that favor wet conditions, but the economic forecast for certain crops in that category might provide a disincentive. There is a wide range of potential users of climate forecasts; however, the application of climate information can become complicated when all of the relevant social, biological, and physical factors are brought together. For example, there are cases in which relative benefits vary considerably between individual users and governmental policy objectives, even to the point of being a disincentive in one case and an advantage in another. An existing study of the influence of seasonal to interannual and intradecadal climate variability in the Pacific Northwest, and the extent to which sectors such as water management or forestry might be able to incorporate forecast information, was referenced as an example of how complicated the use of climate information can become. In this instance, early indications are that the intricacies of the social structure may make it extremely difficult even to respond to an early warning. Further studies into the use of climate forecasts will help us to arrive at methodologies for better application of forecasting. Additional support for empirically-based regional studies into the use of climate information as a decision-making tool will help us to make sure that the research in this area is closely tied to the need for information by decision- and policy-makers.

2.4.2 Quantitative assessment of societal impacts of climate variability and change

Rosenberg's review of the MINK (Missouri, Iowa, Nebraska, Kansas) Project, for which he served as one of the principal investigators, provided a useful description of regional integrated assessment. The general objective of an integrated assessment methodology is to link causes and effects of change in order to illuminate issues relevant to decision- and policy-makers. In the MINK study, which was among the first regional integrated assessments of climate impacts, researchers imposed the climate of the 1930s in the U.S. midwest on the same region sixty years later under changed socio-economic conditions. The study considered effects of such a climate analogue on agriculture, forestry, water resources, and energy. Among the most notable features of this study was the inclusion of cross-sectoral, indirect effects, incorporation of assumed adaptation and technological change, and consideration of how future conditions would alter regional vulnerability to climate changes. The biggest impact of the hypothetical 1930s-like droughts in the 1990s was estimated to be on the availability of water for all applications. The water flows in the Missouri, the Upper Mississippi, and the Arkansas rivers were estimated to decrease 28%, 28%, and 8%, respectively. Such reductions in water flows would eliminate navigation in the Missouri river. Another major impact of such multiyear droughts in the 1990s was estimated to be on agricultural yield which would be reduced 25% and the gross regional product would decrease 10%. Because the MINK area is responsible for much of the U.S. agricultural production, multiyear droughts in the MINK area would significantly reduce the U.S. agricultural output for many years affecting the U.S. and world food supplies.

A team, including **Rosenberg**, is working on the development of the Global Change Assessment Model (GCAM), which is an analytical tool to support integrated assessment. GCAM is a suite of modeling tools that interact to analyze four integrated sets of processes: human activities, atmospheric composition, climate and sea level, and ecosystem. Whereas the MINK study relied on the use of an analogue climate, GCAM will both draw on results from Global Climate Models as information sources and will rely more directly on submodels of the ocean carbon cycle and atmospheric chemistry.

Integrated assessment methodologies are still in an early stage, but are beginning to yield insights able to contribute to broader policy debate. On the matter of the type of information derived from Global Climate Models, including levels of specificity, **Rosenberg** stressed the point that uncertainties are implicit and exist at all levels in almost every modeling system, and users must take this into account. Having said that, the impacts modeling community is always looking to the physical science community for further information regarding what we can trust and what we can not. The impacts modelers hope to provide to the climate modelers useful information regarding precisely where the reduction of uncertainty regarding the climate system might have the highest return in terms of social welfare. For example, it appears that humidity may be as important as temperature to the impacts community and therefore reducing uncertainty related to humidity projections could be most useful to populations in climate-sensitive regions.

The GCAM approach need not be limited to questions of climate change alone. With the support of NASA and NOAA, a consortium of Canadian, U.S., and Mexican natural resources and economic modelers are employing the GCAM methodology to determine the sensitivity of North American agriculture to interannual and interdecadal climate variability and the socio-economic consequences of these sensitivities.

2.4.3 Climate variability and public health

The extent to which climate variability influences environmental conditions conducive to the emergence and spread of infectious diseases has become an active area of interest for physicians and climate scientists alike. A more sophisticated understanding of the connections between climate and diseases could make an important contribution to the early warning capabilities of public health infrastructure, and will certainly require collaborative attention from physical scientists, biologists, social scientists, and physicians. In terms of societal impacts of climate-related health concerns, two principal issues were covered: how can climate variability contribute to the emergence and spread of infectious disease, and how could predictive understanding of climate variability help to head off the spread of disease.

Preliminary indications of a climate-disease connection have begun to emerge. The vector responsible for dengue fever, for example, aedis aegypti mosquitoes, is now found in latitudes higher than usual. Malaria is now detected higher in the highlands of central Africa. Studies of the effects of a potential CO_2 doubling in terms of epidemic potentials indicate that vectoral capacity would change. Some examples of disease outbreak coincident with the anomalous climate conditions of the early 1990s include: the outbreak of cholera in South America in 1991, dengue fever in 1993-94 in Costa Rica, and the outbreak of cholera in Bangladesh in 1993. At higher latitudes, extreme heat killed a record number of people in Chicago in 1995 and equine encephalitis emerged in the northeast U.S. again in 1991-93.

The climate questions most in need of study are centered around the trends and rates of fluctuations in climate, as well as the time scale (e.g. whether anticipated fluctuation is seasonal, interannual, or decadal). Research that considers the effects of tropical ocean warming and potential shifts in the climate regime within a context of marine and terrestrial biology is essential to the climate-health connection. To what extent warmer temperatures affect the rates of reproduction, and growth or evolution of opportunistic pests, parasites, and pathogens needs to be understood prior to an ability to make appropriate use of predictive climate information. Even with the capacity to anticipate climate trends, the climate-ecosystem interactions will necessarily have to be studied within a context of such socio-economic factors as urbanization and general level of economic development in order to begin to analyze the interactions amongst factors that will lead to the emergence of infectious diseases.

Once we have a better understanding of the nature of the interaction between climate and the ecological factors that contribute to disease outbreak, forecasts of seasonal to intradecadal conditions combined with further information, even predictions to the extent possible, of the propensity for extreme events, will provide the most useful "early-warning" tools. Extreme events are potential triggers for outbreak: flooding breeds fungi, drought conditions followed by rains provide conditions amenable to locusts, and anomalous shifts in wet and dry conditions can alter predator-prey relationships important to the control of vector populations.

Forecasts of climate anomalies and preparations to mitigate their effects will not eliminate the threat, but there are a number of measures that can be taken by public health officials in advance to address conditions that make it easier for disease to spread. For example, bioremediation options exist if mosquito larvae are the target; an option far superior to wide-spread spraying of adult mosquitoes. Early warning can also help public health officials make optimum decisions and afford time to inform physicians that they may be seeing symptoms associated with specific infectious diseases which leads to better treatment.

On the subject of what model-based climate information would be very useful, **Epstein** offered that in the near term the most useful information would be projections of extreme rain events. A retrospective analysis of climate trends leading up to the outbreak or spread of climate-sensitive infectious diseases would also be helpful to the larger effort to advance understanding of climatically-sensitive ecological conditions conducive to the spread or emergence of vectors and viruses.

3. Workshop conclusions and recommendations

3.1 Conclusions

The results of the preliminary analyses of observations and model experiments presented in the Workshop, and previously published literature on this subject were discussed by the Workshop participants.

- The relative shortness and quality of the instrument-measured climate record only allows us to quantify characteristics of climate variability at time scales up to 10-20 years.

- There are several phenomena exhibiting climate variability at decadal time scales, some of which appear to have distinct time scales and some appear to have "red noise" characteristics. The following phenomena appear to be the most promising for understanding and developing predictive skill.

  1. The El Nino-Southern Oscillation (ENSO),
  2. The tropical Atlantic SST and the associated climate variability over the tropical Atlantic, the Americas, and Africa,
  3. Wind-driven ocean circulations (North Atlantic and North Pacific) and their interaction with the atmosphere,
  4. The North Atlantic thermohaline circulation and its interaction with the atmosphere.

- There is some predictability inherent in the persistence attached to the slow time scales of some components of the climate system, in particular, the oceans and sea ice. However, To enhance understanding and predictive skill, it is very important to determine whether these promising phenomena exhibit distinct decadal oscillation time scales.

- An improved understanding of natural decadal variability is needed to distinguish anthropogenic climate change from natural variations.

- Several global coupled ocean-atmosphere models simulate various aspects of some of the observed decadal time scale phenomena.

- Three of the decadal time scale phenomena (the North Atlantic thermohaline circulation variability, the tropical Atlantic SST variability, and the tropical Pacific SST variability) appear to be potentially predictable at lead times of several years because they exhibited dominant oscillation periods during the analysis period. Predictability of the thermohaline circulation variability was studied using a global coupled ocean-atmosphere model and predictability of the tropical SSTs was studied using statistical models fitted to SST observations.

- Many of the global climate models in current use do not adequately represent the processes likely to be important in decadal climate variability, and its interactions with interannual variability and anthropogenic climate change.

- Hurricane damage potential in the U.S. and the Caribbean countries has exhibited decadal-multidecadal variability.

- The world food and water supplies may be vulnerable to decadal time scale climate variations.

In addition to the above phenomena, there are interesting decadal-multidecadal climate variabilities over the Arctic and northern Eurasia, the Asian-Australian monsoon region, and southern Africa. It is not obvious, however, from the preliminary work on these variabilities that they are distinct phenomena having large spatial scales and distinct time scales. It is possible that the above list of promising phenomena will change over the course of this program as more characteristics of the decadal-multidecadal climate variabilities in various parts of the world are better known.

3.2 Recommendations

Based on the agreed-upon conclusions, it was decided to make the following initial recommendations to national and international funding agencies, and the International CLIVAR program.

Recommendation 1:

In view of the possible predictability of the decadal climate variability phenomena and their impacts on the society, it was the consensus opinion of the participants that a research and applications program should be organized to reconstruct the past decadal variability from the instrument-measured and paleoclimate data; to understand mechanisms of decadal climate variability; to assess its potential predictability; to develop models that realize its potential predictability; and to apply the predicted information for societal benefits. This program should be a major component of the DecCen component of International CLIVAR program.

Recommendation 2:

This program should focus on the decadal variability of

1. the ENSO,
2. the tropical Atlantic SST and the associated climate variability over the tropical Atlantic, the Americas, and Africa,
3. wind-driven ocean circulations (North Atlantic and North Pacific) and their interaction with the atmosphere,
4. the North Atlantic thermohaline circulation and its interaction with the atmosphere.

The first two phenomena should be accorded the highest priority since they appear to be the most promising for understanding and prediction.

Recommendation 3:

Past decadal time scale variability should be reconstructed using the available instrument-measured and paleoclimate data. For understanding and prediction, it is important to determine whether the above-mentioned observed phenomena occur at preferred decadal oscillation time scales.

Recommendation 4:

Comprehensive global climate models should be developed that adequately represent the processes likely to be important in decadal climate variability, and its interaction with interannual variability and anthropogenic climate change. Such models should be free from artificial intervention in the evolution and variability of the model climate.

Recommendation 5:

Predictability and applications studies should be integral components of the program.

Recommendation 6:

The following program elements are proposed to achieve these goals.

1. Organization of instrument-measured and paleoclimate time series
2. Development of dynamical models suitable for the study of decadal climate variability and its predictability
3. Diagnostic and model-evaluation studies with the instrument-measured and paleoclimate data, and dynamical models
4. Predictability studies using statistical and dynamical models
5. Applications feasibility studies
6. Long-term monitoring of the decadal variability phenomena and observing system simulation studies

Recommendation 7:

The program should be implemented via the following near-term action items.

1. Locate, collect, quality-check, and document instrument-measured time series of climate quantities; and create interconnected Internet Web sites pointing to such data.
2. Locate, collect, quality-check, and document paleoclimate data, reconstruct equivalent surface temperature and precipitation from the paleoclimate data; and create interconnected Internet Web sites pointing to such data.
3. Develop comprehensive, very high resolution, global coupled ocean-atmosphere-land models without artificial interventions.
4. Test and evaluate these models rigorously for their ability to simulate the annual cycle, the ENSO, and the various decadal climate variability phenomena.
5. Conduct carefully designed model experiments to address the science questions relating to the various instrument-measured and paleoclimate data and to identify "targets" for modeling and prediction studies.
6. Conduct studies of decadal predictability with statistical and dynamical models to estimate forecast skill and lead time for the various decadal variability phenomena.
7. Make all model output widely available for analysis.
8. Form a panel consisting of decadal variability researchers, applications experts, and government officials to develop an integrated applications studies program and to monitor its progress.
9. Set up an observing program component for long term monitoring and specialized observations of the decadal climate variability phenomena.
10. Organize Workshops every two years to assess the progress of the program.

4. Proposed program on decadal climate variability

4.1 Program elements

The following program elements are proposed to achieve these goals.

1. Organization of instrument-measured and paleoclimate time series
2. Development of dynamical models suitable for the study of decadal climate variability and its predictability
3. Diagnostic and model-evaluation studies with the instrument-measured and paleoclimate data, and dynamical models

4. Predictability studies using statistical and dynamical models
5. Applications feasibility studies
6. Long-term monitoring of the decadal variability phenomena and observing system simulation studies

4.2 Implementation

Specific recommendations for implementing this program are made in this Section for each program element.

4.2.1 Organization of instrument-measured and paleoclimate time series

4.2.1.1 Instrument-measured time series

Exploratory analyses of instrument-measured climate quantities have been very useful in uncovering potentially important climate variability phenomena at time scales longer than a few years, but these studies have not revealed much quantitative information about the characteristics of decadal variability in each region and about inter-relationships, if any, among the decadal variability in various parts of the world. It is very important to know if there are inter-relationships among the decadal variability phenomena identified earlier in order to understand the mechanism(s) and predictability of decadal climate variability.

Data sets such as the Global Ocean Temperature Atlas (GOSTA) and the Comprehensive Ocean-Atmosphere Data Set (COADS) contain surface temperatures and some other variables only over the Oceans. Even though rainfall, surface air temperature, soil moisture, atmospheric temperature, and wind data over many land regions are available in centralized archives (for example, at NCAR), a concerted collection, quality check, and analysis effort is necessary to obtain the best possible quantitative information about decadal climate variability in various parts of the world. Therefore, there should be a centralized CLIVAR catalog and information location of all instrument-measured climate variables. All such data do not have to reside on the same computer but there should be a central source of information about individual archives pointing to the various Internet Web sites from where the data can be obtained. There should be uniformity in documentation of these data. Much of the archived data were collected by national Weather Services for purposes other than climate analysis and prediction, therefore a rigorous data quality check is required to make the data quantitatively usable for the analysis and prediction of decadal climate variability. Appropriate station data should also be objectively analyzed to form gridded data.

One such collection and quality check effort is already under way for oceanographic measurements. A project sponsored by the Intergovernmental Oceanographic Commission, known as the Global Oceanographic Data Archeology and Rescue (GODAR), has been successful in locating and digitizing more than 1.2 million historical ocean temperature profiles. These data extend ocean data coverage in both space and time. The success of this data collection project has allowed description of upper-ocean temperature variability on gyre and basin scales, and on interannual to decadal time scales not previously possible. An additional 600,000 temperature profiles collected as part of the GODAR project are now being processed and will be distributed by early 1997. More than one million Nansen profiles and 500,000 bathythermograph profiles in manuscript form have been identified by the GODAR project. The GODAR project is an example of international cooperation in ocean data location and management that can serve as a model for the CLIVAR climate data location, collection, and quality check program recommended by this Workshop.

As found in the GODAR project, there may still be a large amount of surface climate data available in manuscript form in the archives of national Weather, Agricultural, and other such Services. Every effort must be made to locate and collect such archived data. The data location, collection, and documentation effort might turn out to be the most important contribution of the International CLIVAR program to climate research at decadal time scales.

The GODAR project is also an example of how various national organizations possessing the data can facilitate research programs that would eventually benefit the global society. The recent stance adopted by some national organizations to sell data to individual researchers is definitely not conducive for the implementation of an international program such as CLIVAR.

4.2.1.2 Paleoclimate time series

As mentioned earlier, typical time series of instrument-measured surface climate variables are approximately 100 years long. Moreover, even 100 years long time series of acceptable quality measurements are not available in many parts of the world. The time series of sub-surface ocean temperature and salinity are only a few decades long where available. Tree-ring and coral records from long-lived trees and corals can be used to infer information about climate variability at the site of the trees or corals. Examples of decadal climate variability over the U.S. and the tropical Pacific inferred from long tree-ring and coral records, respectively, were shown in this Workshop. The main paleoclimate data sets of interest are those with annual or preferably subannual resolution for the past 2000 years. Such data are archived at, among other Centers, the National Geophysical Data Center in Boulder. An exhaustive effort should be made to check the quality of the archived data and document them as uniformly as possible. The paleoclimate indicators should be converted to equivalent surface temperature and precipitation, and made available for analysis wherever possible. This conversion will also extend the instrument record backwards in time in regions where both instrument-measured and paleoclimate data are available. All paleoclimate indicators and the derived quantities do not have to reside on the same computer, but the distributed Internet Web site model recommended earlier for the instrument-measured data can be used.

4.2.2 Modeling program

4.2.2.1 Development

Modeling will be a very important component of the decadal variability program. Modeling is crucial for understanding the mechanisms of decadal climate variability and studying its predictability. Modeling is also very important for studying the interaction among the natural interannual and decadal climate variability, and anthropogenic climate change. Decadal climate variability has been explored so far with low-resolution, global coupled/uncoupled ocean-atmosphere-land surface models developed mainly for studying anthropogenic climate change; with models developed to study the ENSO phenomenon; and with process models. Although the exploratory studies are encouraging, the science and applications requirements of this program will not be satisfied unless global coupled/uncoupled ocean-atmosphere-land surface models are developed specifically for these requirements.

Many of the current global climate models were based upon the previous generation of atmospheric weather prediction models and some variant of the Bryan-Cox global ocean model. Although these climate models have been a very important first step in the evolution of climate modeling, it is obvious that new approaches, perhaps different from weather prediction models, must be used to take the next step in modeling climate variability. Based on experiences with the current global climate models, it appears that some of the requirements of the global climate models to be developed specifically to study variability at interannual to century time scales are freedom from artificial interventions such as 'flux adjustment', ocean conditions restored to prescribed values in the Arctic and the Antarctic, and poorly understood parameterizations of ocean mixing; high-enough spatial resolution to resolve important phenomena such as equatorial ocean waves, western boundary currents, ocean convection at high latitudes, and the ITCZ; high computational speed to facilitate ensembles of multicentury integrations; 'plug compatibility' of the constituent components and modules; uniformity in model outputs for relatively easy intercomparison; and physically-based schemes of 'spin-up' and initialization.

The study of decadal and longer time scale climate variability, natural and anthropogenic, requires multicentury long integrations of the coupled/uncoupled ocean-atmosphere-land models. Due primarily to mismatches between the fluxes provided by the atmosphere model and those required by the ocean model to maintain its climatology, the climate of a coupled ocean-atmosphere system deteriorates from that simulated when the two components are integrated separately. In some of the current global climate models used for studying anthropogenic climate change and decadal climate variability, this problem is mitigated by adjustment of heat and freshwater fluxes. The aim of this device is to obtain an average annual cycle of the model climate that is close to the average observed annual cycle. This so-called 'flux adjustment' allows multicentury long experiments with the global climate models but its role in the model-generated climate variability and change is not known. In the next generation of global coupled ocean-atmosphere-land models developed specifically to study decadal and longer term climate variability, 'flux adjustment' must not be used. It might help if a global coupled model is developed as one entity and, if necessary, 'tuned' as one entity.

One of the major causes of decadal and longer time scale climate variability is likely to be the variability of thermohaline ocean circulation. The convection that causes this circulation occurs in regions that are only a few square kilometers in area. A global ocean model must include this high-resolution phenomenon in order to have a realistic thermohaline circulation. Therefore, either the model should be integrated on a high-enough resolution grid (which, in the near term, is not practical) or some other way such as adequate parameterization of the convection must be found for this purpose. Another likely cause of decadal climate variability is the nonlinear instability of western boundary currents. These ocean currents are typically 10-100 kilometers wide, so a global ocean model must have adequate grid spacing to resolve these currents. Studies of interaction between decadal and interannual climate variabilities also require high resolution ocean models because equatorially-trapped ocean waves are associated with the major interannual variability phenomenon, the ENSO. Therefore, the spatial resolution of the ocean model should be high enough, at least near the Equator, in the convection regions, and in the boundary current regions, to resolve these important phenomena.

The atmosphere models also must have high resolution. Accurate simulations of the Inter-Tropical Convergence Zone (ITCZ) are required since the ITCZ is likely to be playing an important role in the decadal variabilities of the ENSO and the tropical Atlantic climate system. High resolution may also be required for the midlatitude atmosphere to respond to underlying SST anomalies via modification of baroclinic eddy activity. The small-amplitude but long-lasting decadal anomalies in precipitation, surface air temperature, surface air humidity, and soil moisture must be simulated and predicted accurately to be useful in societal applications. The study of the impacts of climate variability on public health also requires atmospheric conditions in the first kilometer from the surface. These requirements predicate high-enough resolution atmosphere models and realistic representations of convective and other types of clouds, cloud-radiation interaction, the atmospheric boundary layer, and ground hydrology. Since the freshwater from the mid-high latitude river runoff is likely to be important in the oceanic thermohaline circulation and its variability, the ground hydrology model must be able to estimate river runoffs reasonably accurately. Another source of freshwater at high latitudes is sea ice which is also very important in controlling ocean-atmosphere heat transfer. Both thermodynamics and dynamics of sea ice must be modeled reasonably accurately.

Although the above arguments indicate the need for high resolution in the atmosphere and ocean of a climate system model in order to better represent the physical processes involved, there is a trade-off between resolution and the duration of run possible with a given model because of restrictions on computer time. Consequently, there is also a case to be made for longer runs of somewhat simpler or lower resolution models as part of a hierarchy of models that help to develop understanding of what is going on in both the real world and the more complex models.

Statistical 'conversion' systems are developed for some global weather forecasting models, which use much higher resolution than climate models, to make their outputs suitable for local weather forecasting. It may be necessary to develop such statistical 'conversion' models to make climate model outputs suitable for local applications.

4.2.2.2 Evaluation-intercomparison

4.2.3 Diagnosis program

4.2.3.1 Analysis of instrument-measured and paleoclimate time series

Exploratory analyses of some of the available instrument-measured and paleoclimate data have revealed some very interesting aspects of decadal climate variability. The results contained in the CLIVAR Science Plan and also those presented in this Workshop have sharpened the science questions to be addressed to the instrument-measured and paleoclimate data. These questions include:

1. Is the data quality adequate to quantify characteristics of decadal climate variability?
2. Are there preferred decadal time scales or is it all 'noise'? What are the implications of this for potential predictability of decadal climate variability?
3. Are the decadal variabilities in various parts of the world inter-related?
4. Do we have adequate information from the data analyses to compare with model-simulated decadal variability?
5. Do the data analyses give us indications of mechanisms of decadal climate variability?

4.2.3.2 Analysis of model experiments

The purpose of the model diagnostics program should be two-fold; to simulate the observed decadal variability phenomena and understand the mechanisms that cause them, and to evaluate the simulation's usefulness for societal applications. The advantages of a model-generated data set over an instrument-measured or paleoclimate data set are that all variables necessary to understand the mechanism(s) of a phenomenon may be available and that the time series of the model-generated data can be, in principle, infinitely long. Such long integrations require a large amount of CPU time on supercomputers and large-capacity storage devices for the output data. Such resources are available mostly at national climate research Centers and the majority of the climate research community has only limited access to such models and their output data. The national research Centers are not equipped to thoroughly analyze their model output to evaluate their models accurately. Therefore, the model output data should be made widely available to the climate research community. It is hoped that mutually-beneficial relationship between the modelers and analysts will develop as a result of this program.

The following questions should be addressed to the model outputs.

1. Do the models simulate the observed decadal variability phenomena identified from the analyses of observations?
2. Are there preferred decadal time scales or is it all 'noise'? What are the implications of this for potential predictability of decadal climate variability?
3. Are the decadal variabilities in various parts of the world inter-related?
4. What are the mechanisms of decadal climate variability in atmosphere-only, ocean-only, and coupled ocean-atmosphere models?

5. Are the decadal anomalies in tropospheric and upper ocean climates predictable? If so, how far in advance and with how much skill?
6. How are decadal anomalies in surface climate related to those in tropospheric and upper ocean climates?
7. Are the decadal anomalies in land surface climate predictable? If so, how far in advance and with how much skill?
8. Do the interannual and decadal variabilities interact? How?
9. Does this interaction make each more or less predictable?
10. Do the decadal variabilities interact with anthropogenic climate change? How?
11. Does this interaction make each more or less predictable?
12. Does the deep ocean play any role in generating decadal variability of surface climate?

4.2.4 Predictability and prediction studies

Perhaps the strongest motivation for studying decadal climate variability in spite of the relative shortness of the observational record and the need to perform very long model integrations is the possibility that decadal climate variability may be predictable with some skill at relatively long lead times. As argued earlier, the societal applications of such predictions may be substantial.

The predictability studies should be conducted with statistical and dynamical models of the decadal variability phenomena identified earlier. Since decadal climate forecasts can not be verified for several years after making them, it will be very important to conduct retrospective prediction studies with the statistical and dynamical models to build confidence in decadal climate forecasts after the predictability of a decadal variability phenomenon is estimated.

Dynamical models have several advantages over statistical models for making predictions. The advantages are (1) global domain, (2) many internally-consistent variables including surface climate variables useful for applications, and (3) possibility of predicting future evolution of "event-like" long-lived climate anomalies such as the Great Salinity Anomaly.

4.2.4.1 Statistical models

Statistical models of various types fitted to observations have been used extensively to make long range weather and short term climate forecasts. It assumes that "the past is the future", i.e. the past observational record contains enough information about the phenomenon to make a successful forecast of its future evolution. The statistical forecasting technique does not require supercomputers and it is relatively easy to make ensemble forecasts with several models. A statistical forecast, of course, has to be limited to geographical regions where the observed quantities are available and to the available observed quantities.

Over many parts of the world, long time series of surface temperatures (land and ocean) and/or rainfall are available. The choice of statistical models may depend on the characteristics of decadal variability revealed by rigorous analysis of these time series. The forecast skill level may be higher and the lead times may be longer if there is a preferred decadal time scale in the time series. Some type of filtering to remove high-frequency noise may also be necessary to increase the lead times and forecast skill levels. The statistical predictability and prediction studies may be more important in the immediate future to assess the prediction impact on societal applications and until the required coupled ocean-atmosphere-land models are developed.

4.2.4.2 Dynamical models

As mentioned earlier in section 2.3, climate predictability at decadal time scales may be higher if there are coupled ocean-atmosphere modes with preferred decadal time scales. In such cases, dynamical coupled ocean-atmosphere models may be very useful prediction tools if they can simulate the decadal coupled modes. The only clearly identified coupled ocean-atmosphere mode is the ENSO and dynamical coupled models of various complexity routinely make skillful forecasts of it several seasons in advance.

The Diagnosis program (section 4.2.3) should identify decadal coupled ocean-atmosphere modes if there are any in the instrument-measured time series and in model-generated data sets. Extensive predictability studies should then be carried out with coupled ocean-atmosphere models of various complexity. "Spin-up" and initialization of these models, and sensitivity of the predicted decadal modes to initial conditions should be the focus of these experiments.

To capitalize on the predictability, prediction schemes need to be developed that include considerations of observations and their analysis, initialization of models, use of statistical and physical models, and products.

4.2.5 Applications studies

The world foodgrain and water supplies may be vulnerable to droughts lasting many years. As a consequence, economic, social, and political systems in industrialized and large-population agrarian-industrial countries may also be vulnerable to such droughts. Therefore, there should be applications studies to assess such vulnerabilities, estimate the necessary prediction skill and important quantities to mitigate/exploit climate anomalies lasting many years, and develop mechanisms whereby skillful predictions can be used for societal benefits.

It is recommended that a panel of experts consisting of decadal climate variability researchers, those involved in applications and social sciences, and government officials be formed to develop an integrated applications studies program and to monitor its progress. This panel should identify the decadal variability phenomena that are clearly relevant to societal applications, the associated impacts, the vulnerabilities of socio-economic systems, and the possible actions (mitigation and adaptation). The potential prediction skill and lead times of these phenomena should be estimated, and the usefulness of the predictions to specific applications areas should be assessed. High government officials of the potentially vulnerable countries should be involved from the beginning of the program in the process of developing applications strategies. It will be very important to know from the beginning of the program if these countries will participate in estimating which quantities should be predicted and with what skill levels, whether the predicted information will be used if provided at the necessary skill level, and if the beneficiary countries will be willing to fund research and development programs on decadal climate variability. Their co-operation and enthusiastic participation will be vital in the success of this program.

4.3 Priorities

The long-term program, as recommended above, is too diverse and large in scope to be executed with the very limited resources that are likely to be available in the initial stage. Therefore, it is necessary to prioritize science questions and action items in order to make the most cost-effective use of the available resources. Also, it is necessary to convince the scientific community, national funding agencies, national and international policy makers, and the applications community that the research on understanding and prediction of decadal climate variability is a scientifically exciting and societally beneficial endeavor.

From the presentations and discussions in the Workshop, it appears that exploration is farther advanced in two of the phenomena recommended for further study, viz. the decadal-multidecadal variability of the ENSO and the decadal-multidecadal variability of the tropical Atlantic region climate, than the others. Also, reasonably convincing links between these two phenomena and regional/global decadal-multidecadal climate variability appear to exist, making these two phenomena very important for societal impact studies. National and international research Programs such as CLIVAR-GOALS and PACS are already under way addressing interannual climate variability associated with the ENSO and the tropical Atlantic SST variability, therefore according the highest priority to decadal-multidecadal variability of these two phenomena will ensure a reasonable extension and connection to longer time scales.

The preliminary analyses of instrument-measured and paleoclimate data, presented in the Workshop, showed the presence of decadal-multidecadal variability in the tropical Pacific and Atlantic climate systems. Several plausible mechanisms of these variabilities were suggested. One of the plausible mechanism is the generation of low-frequency climate variability as a component of "red noise" spectrum due to "white noise" forcing of the high-inertia ocean by the atmosphere. This is usually assumed to be the "null" hypothesis in testing statistical significance of spectral peaks. If there are distinct time scales of oscillation, there may be some other mechanism(s) at work perhaps involving some intrinsic time scales in the climate system. This also has important implications for potential climate predictability. If the variability is of the "red noise" type, evolution of a climate anomaly may be predictable with some skill upto the persistence (de-correlation) time after the onset of the anomaly. If the regional/global climate system oscillates at distinct time scales, however, there may be potential predictability upto one oscillation period or longer at reasonably high skill levels. Therefore, it is crucial for understanding and prediction of decadal-multidecadal climate variability to find answers to the questions,

> Are there distinct decadal-multidecadal time scales at which regional/global climates tend to oscillate? If yes, why?

There are several nuances to these questions and individual researchers should be free to devise their own techniques to address them.

As is generally well-known and was discussed at length in the Workshop, most instrument-measured time series contain only a few samples of decadal-multidecadal variability. Some paleoclimate time series are many hundred years long and they can be used, in conjunction with the shorter instrument-measured time series, to address the questions posed above. Therefore, it would be necessary to organize, quality-check, and documentation of instrument-measured and paleoclimate data from the tropical Pacific and Atlantic regions to address the above questions. The details of this data organization effort are described in section 4.2.1.

These questions can also be addressed with specifically designed experiments with hierarchies of atmosphere-cryosphere-biosphere models. Models perhaps will be the only useful tools to understand and predict decadal-multidecadal climate variability. The recommended modeling, diagnostics, and predictability studies are described in sections 4.2.2, 4.2.3, and 4.2.4.

Justification for prioritizing decadal variability phenomena

	ENSO	Tropical Atlantic
Scientific justification and rationale	Large space scales; perhaps distinct time scales; interannual predictability affected by decadal variability; world-wide impacts	Large space scales; distinct time scales; impacts on the climate over the Atlantic, the Americas, and Africa
Readiness and feasibility	Long, instrument-measured time series not available; long time series of proxy indicators available; model validation possible; temperate climate for year-round observations	Relatively long instrument-measured time series available over the Ocean and adjacent continents; model validation possible; temperate climate for year-round observations
Probability for multiple pay-offs	Yes	Yes
Collaboration with other programs	TOGA-TAO, PACS	PIRATA, PACS
Balance of activities	Empirical studies, modeling, field programs	Empirical studies, modeling, field programs
Contributions to more than one CLIVAR sub-programs	GOALS, ACC	GOALS, ACC

As mentioned earlier, the decadal-multidecadal variabilities of the ENSO and the tropical Atlantic climate variabilities have been associated with variability of regional/global climate. It is not known, however, whether successful decadal climate forecasts can be translated to mitigation/exploitation of the anomalous climate impacts on society. Therefore, the same high priority given to addressing the science questions should be accorded to addressing the questions of assessing societal vulnerability to decadal climate variability and applicability of decadal climate forecasts to societal impacts.

The earlier-mentioned diagnostic studies should result in better quantification/identification of characteristics of decadal variability of land and ocean surface climate since the archived, long time series are of surface climate quantities. The paleoclimate data will also provide information about decadal variability of land surface climate. In order to understand mechanisms of decadal climate variability, especially the roles of ocean-atmosphere interaction and ocean dynamics, long-term measurements of temperature, velocity, and salinity of surface and subsurface ocean are required. An array of buoys for such measurements, the TOGA-TAO array, already exists in the equatorial Pacific and planning for a pilot project, the PIRATA, to install such an array in the equatorial Atlantic is well under way. The preliminary analyses of long time series of SST measurements in the tropical Pacific and Atlantic Oceans indicate that the decadal signal is strongest in the tropics-subtropics and not at the Equator. If these results are confirmed by more detailed analyses of the archived data, the TAO and PIRATA arrays should be expanded to include the tropical-subtropical regions of the Pacific and Atlantic Oceans, and should be maintained permanently.

As the foregoing shows, decadal time scale climate variability is a scientific problem whose time has come and whose impacts on the global society are perhaps longer lasting and therefore more serious than the impacts of interannual climate variability. The two recommended high priority phenomena promise large returns in terms of challenging science and societal benefits if adequate resources are invested in this program. Of the other potential phenomena, decadal variability of the North Atlantic and North Pacific climates has already attracted serious attention from researchers. The field of decadal climate variability is evolving rapidly, requiring at least one annual meeting devoted to this subject. In the next few years, the list of high-priority phenomena may change, but the field of decadal climate variability and its societal impacts will continue to be more and more important . It is hoped that the preliminary results presented in this Workshop and the enthusiasm of participants will convince funding agencies to invest the necessary resources in this program.