DATA REQUIREMENTS FOR DECADAL-TO-CENTENNIAL CLIMATE VARIABILITY STUDIES AND COUPLED MODELS

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1 - INTRODUCTION

The study of natural variability of the climate system at decadal-multidecadal timescales has a long history but is receiving increased attention over the last two decades. During much of its history, this field was mired in controversy because the majority of decadal climate variability studies were confined to sunspot cycle-terrestrial climate variability correlations. But this field has now emerged from this controversy and is fast becoming an important area of climate research because

- decadal-multidecadal climate variability affects the lives of several billion people via its long-lived effects on agriculture, water resources, fisheries, and public health;
- ENSO and the Asian-Australian monsoons, and their predictabilities are known to vary at decadal-multidecadal time scales;
- natural climate variability at decadal-multidecadal time scales has the potential to interact with and interfere in an unambiguous detection of anthropogenic climate change; and
- it is possible/likely that some societies are more vulnerable to decadal climate anomalies than to shorter-term climate anomalies because of those societies' resilience against shorter-term climate anomalies.

As an indication of its importance, several national and international Workshops on decadal climate variability have been organized in the 1990s to assess the progress of research in this area and to develop research programs. One of the major components of the International CLIVAR project, organized by the World Climate Research Program, is the study of decadal to centennial scale climate variability.

Almost all our quantitative knowledge of decadal-multidecadal climate variability is based on analyses of surface (land and ocean) observations during approximately the last one hundred years. These analyses of available instrument-measured and paleo-climate data indicate that much of the decadal-multidecadal climate variability over land areas appears to result from ocean-atmosphere interactions. The oceans, with their large mechanical and thermal inertias, and decadal-multidecadal timescales characteristic of basin-scale ocean circulations, appear to be at the center of almost all observed decadal-multidecadal climate variability phenomenons.

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Sea surface temperature (SST) variability in various parts of the world at decadal-multidecadal timescales is associated with climate variability over the oceans and over land areas at decadal-multidecadal timescales. Therefore, it is very important to study air-sea interaction and ocean-only processses that are responsible for decadal-multidecadal SST variability. Information about decadal-multidecadal climate variability phenomenons, obtained from analyses of observations and model experiments, and their likely mechanisms are briefly described in section 2. Ocean data requirements to further study these phenomenons and assess their predictability are described in section 3. Some of the major challenges that will have to be met in designing and implementing an ocean observing system to study decadal-multidecadal climate variability are described in section 4, and an attempt at prioritizing the implementation of such a system is made in section 5.

2 - PHENOMENONS AND THEIR LIKELY MECHANISMS

The most intractable problem of diagnosing characteristics of decadal-multidecadal climate variations is insufficient quantity and unreliable quality of instrument-measured data. The longest, instrument-measured time series are those of surface temperatures (land and sea) and rainfall over land areas. Century-long time series of land surface temperatures have adequate spatial coverage only in some areas of Northern Hemisphere and are contaminated by anthropogenic influences. Century-long time series of SSTs have adequate spatial coverage only in some oceanic areas, primarily in the North Atlantic and tropical South Atlantic,and are contaminated by changes in measurement techniques. Rainfall data also suffer from some of these problems; moreover, rainfall is highly inhomogeneous in space and time. Despite these problems, there have been several attempts to extract spatial and temporal characteristics of decadal-multidecadal climate variations, primarily in the Atlantic and neighboring land areas, using the available surface temperature and rainfall data sets. Attempts are also being made to fill spatial and temporal gaps in the basic SST data sets such as COADS and GOSTA by objective-analysis (e.g., GISST SST and sea-ice data set, GISS rainfall data set) and projection (e.g., Kaplan et al. SST and sea level pressure data sets) techniques. Analyses of the basic and derived data sets have revealed several regional patterns of decadal-multidecadal climate variations and now evidence is emerging that some of these regional patterns may be components of global-scale, decadal-multidecadal climate variations.

2.1 - Global scale decadal-multidecadal climate variations

One of the major questions that is being posed to these instrument-measured data sets is, "how important are decadal-multidecadal climate variations?" Variance analyses of the GOSTA SST data and the GISS rainfall data show that upto 50% of the SST variance and 40% of the rainfall variance on continents are contained at periods greater than 8 years, approximately equally divided between 8-15 years and greater than 15 years periods. The amounts of fractional variances 'explained' by distinct, physical modes of decadal-multidecadal variations and the background spectrum,however, are not known. A question implicit in this is if there are statistically-significant spectral peaks which would indicate that some decadal-multidecadal timescales are more important than what an assumed background spectrum might suggest. If there are such spectral peaks, there may be some physical processes other than those responsible for the background spectrum at work and such spectral peaks would suggest a potential for long-term climate predictability. Statistically-significant decadal spectral peaks have been found in the analyses of some of the basic data sets in the tropical South Atlantic and high-latitude North Atlantic regions. Decadal-multidecadal spectral peaks or 'bumps' that are not highly significant have also been found in other parts of the world, but their reliability is uncertain. Since almost all the available instrument-measured time series are not long enough to satisfactorily answer this question even about decadal timescales, the question of multidecadal spectral peaks must be considered even more open. Neverthless, these peaks and 'bumps', when analyzed in detail, yield some interesting information about decadal-multidecadal climate variations.

Analyses of some of the basic and derived data sets show that there are global-scale, decadal (8-15 years) and interdecadal (18-23 years) variations in SST, sea level pressure (SLP), rainfall, subsurface ocean temperatures, and near-surface winds. Observational evidence, primarily from derived data sets such as GISST, suggests that spatial patterns at the 18-23 years timescale have a global reflection symmetry about the Equator and a global translation symmetry between the ocean basins. The evidence also suggests that the peak tropical warming in 1900, 1920, 1940, 1960, and 1980 may have been phase-locked to peak solar irradiance. The amplitude of the these warmings was 0.1(C, which is consistent with a black-body response of the Earth to a 0.1% change in solar irradiance. This interdecadal SST pattern also appears to be associated with east-west surface temperature variations in the U.S. and with rainfall variations in China. This SST pattern modulates tropical cyclone activity in the Pacific such that anomalously cold SSTs lead to more tropical cyclones while anomalously warm SSTs lead to fewer but more intense tropical cyclones. In the North Atlantic, variability may occur on even longer (multi-decadal, O(50 yrs)) time scales, which is supported by both model simulations and observations.

Analyses of the GOSTA SST data set, the FSU Pacific wind stress data set, and the GISS rainfall data set show that, at the 8-15 years timescale, SST anomalies in the North Pacific and the North Atlantic evolve in an apparent clockwise rotation around the subtropical gyres in both oceans. The evolution in the North Pacific Ocean appears to lead that in the Indian Ocean and the North Atlantic Ocean by 1-2 years. The amplitudes of these rotating SST anomalies are largest in the tropics. Near-surface, tropical Pacific wind anomalies are physically consistent with the tropical Pacific SST anomalies. Decadal, global rainfall anomaly patterns are strongly associated with these global, decadal SST anomalies, suggesting a potential for long-range prediction of rainfall over continents.

Another interdecadal, global SST pattern, the so-called global change pattern, has also been identified that seems to influence surface temperatures over the U.S. In this pattern, SSTs have been warming in the tropical oceans and cooling in the northern extratropical oceans. Associated with this SST pattern are a warming trend in the western-northwestern U.S., and a cooling trend in the central U.S. and the high-plains region.

2.2 - Decadal-multidecadal variations in the Pacific climate

Analyses of available SST and wind stress observations in the tropical-subtropical Pacific, going back to the early part of the 20th century, indicate that SST and wind stress anomalies appear to travel southwestward from northeastern Pacific near the California coast to the western Pacific "warm pool" region at decadal and longer timescales. These SST anomalies appear to modulate the spatial extent and the SSTs of the warm pool; ocassionally, these SST anomalies then travel northward to the Kuroshio region in the western Pacific. Analyses of observations and coupled ocean-atmosphere model results show that SST and upper-ocean heat content anomalies appear to rotate in a clockwise manner in the middle latitudes-subtropics of the North Pacific. It is not clear, however, whether this so-called North

Pacific Oscillation (NPO) is related to the earlier-described decadal-multidecadal variations in the tropical-subtropical Pacific climate.

2.3 - Decadal and longer timescale variations in interannual ENSO characteristics and in interannual ENSO predictability

The El Nino-Southern Oscillation (ENSO) phenomenon and its influence on the Australian, Asian, and North American climates exhibit strong, decadal-multidecadal variations. Along with these decadal-multidecadal variations in ENSO characteristics and teleconnections, lead times and skill levels of ENSO predictions are also known to vary. ENSO characteristics have been quite anomalous in the last two decades. Two so-called "El Nino events of the century" have occurred in the last 15 years. But, it is not clear from analyses of observations whether this recent anomalous ENSO behavior is due to natural decadal-multidecadal variability or is associated with global warming.

Spatial patterns and annual evolution of El Nino SSTs at interannual timescales are apparently influenced by the decadal-multidecadal vacillations in the warm pool SSTs, described earlier, such that composite patterns of interannual El Nino SST and wind stress extend to the western Pacific when the warm pool is warmer than normal at decadal-multidecadal timescales and are confined to the South American coast when the warm pool is colder than normal. The annual evolution of the interannual Nino3 SST index is much more regular, peaking in November-December, when the warm pool is colder than normal at decadal-multidecadal timescales. These slow vacillations in the warm pool extent and SSTs also modulate the relationship between interannual El Nino SST anomalies and rainfall anomalies over the U.S. and Australia.

Observational results also suggest that the NPO at decadal-multidecadal timescales modulates the magnitude and consistency of ENSO influence in North American climate. Constructive interferences between El Nino-colder phase of NPO and La Nina-warmer phase of NPO is largely responsible for reproducible canonical ENSO signals in North American climate. This variable ENSO-North American climate connection is also apparent in the analysis of Palmer Drought Severity Index (PDSI) and its relationship to ENSO over multidecadal timescales. A drought in the southwestern U.S. during the summer following an El Nino event appears to be a robust feature, but the ENSO-droughts connection in the eastern U.S., southern California, and the Mississippi River valley has fluctuated at multidecadal timescales during this century.

2.4 - Decadal variations in tropical-subtropical Atlantic climate

As discussed earlier, interannual to multidecadal climate variability in the Atlantic region has been the subject of research for a long time, not the least because the longest time series of perhaps the highest-quality instrument-measured data are available for the Atlantic region. Analyses of these data sets have revealed a decadally-varying pattern of SST, surface winds, and sea ice near the northeastern North American coast; multidecadal changes in SST near Newfoundland-Labrador Sea region; occasional incursions of sea ice and salinity anomalies from the Arctic into the North Atlantic; and a dipole pattern of SST and surface winds straddling the Equator in the tropical Atlantic.

The dipole pattern of SST anomalies spanning the tropical-subtropical Atlantic has been a major subject of research because the variability in the cross-equatorial SST gradient has been associated with climate anomalies over neighboring continental regions, especially over northeast Brazil. It has been found that almost 80% variance in coherent decadal fluctuations of this cross-equatorial SST gradient is due to coherent fluctuations in the tropical South Atlantic SSTs at 12-13 years timescales. There are decadal variations in the tropical North Atlantic SSTs also, but decadal SST anomalies in the tropical North and South Atlantic have not always varied coherently over the last 100 years or so. Observations suggest that these decadal SST variations in both hemispheres in the tropical Atlantic may be due to SST anomalies rotating in the subtropical gyres. As mentioned in section 2.1, these rotating SST anomalies in the North Atlantic appear to be connected to those in the North Pacific.

2.5 - Multiyear to decadal timescale NAO-AO-sea ice variations in the North Atlantic

The North Atlantic Oscillation (NAO) is a measure of oscillations in atmospheric mass between sub-polar and sub-tropical latitudes in the North Atlantic region. The NAO is known to play a leading role in orchastrating wintertime weather and climate variations in eastern North America, the North Atlantic, and Europe. During high NAO winters, drier conditions occur over much of central-southern Europe and the Mediterranean, whereas Iceland and Scandinavia experience higher than normal winds from the North Atlantic to Scandinavia and central Europe transports more heat and moisture to these regions resulting in more precipitation and higher temperatures. These changes in the strength and location of winds from the North Atlantic reduce heat and moisture transports to southern Europe and North Africa, resulting in drier and colder conditions over these regions. In the North Atlantic Ocean, the NAO-associated wind and precipitation anomalies influence temperature, rate of oceanic convection, deep-water formation, and primary productivity. Except for the period 1900-1930 and the early-1950s to the mid-1990s, the time series of NAO indices and their spectra exhibit interannual variations without a dominant period of oscillation. During these two epochs, however, more regular NAO variations occurred, with a dominant period at 6-8 years. Some observational studies have suggested associations between North Atlantic SSTs and low-frequency variations in the NAO.

The NAO is also correlated with SLP variations in the circumpolar vortex from monthly to decadal timescales. This so-called Arctic Oscillation has an equivalent barotropic structure and shows a weakening trend over the past 30 years. This trend is consistent with a weakening wind-driven Arctic gyre, a reduction in the winter sea ice extent over the Greenland-Iceland-Norwegian Sea, and an increase in the winter sea ice extent over the Labrador Sea during the past 30 years.

2.6 - Multidecadal-centennial timescale variations in the meridional overturning circulation

Observations of the variability of the meridional overturning circulation (MOC) are rather scarce, since estimates of this quantity entail accurate measurements of the meridional velocity across the Atlantic basin at all depths. One means of providing an estimate of the observed variability involves the use of ocean models driven by observed fluxes at the air-sea interface. A recent study of this type has demonstrated substantial decadal and multidecadal variability of the meridional heat transport at 25N.

2.7 - Mechanisms of decadal-multidecadal climate variability

The major, hypothetical mechanisms of decadal-multidecadal climate variability are, solar irradiance variations, integration of atmospheric forcing by the slower components of the climate system, coupled ocean-atmosphere interactions in the tropics and the extratropics, and variations in the thermohaline circulation. These mechanisms have been shown to cause decadal-multidecadal climate variability in several coupled and uncoupled, ocean-atmosphere general circulation models (GCMs).

It has been shown that either integration of atmospheric noise by the ocean or a coupled ocean-atmosphere mode involving the subtropical gyres and the overlying atmosphere or a combination of the two can generate the observed decadal timescale SST anomalies in the North Pacific and the North Atlantic. The decadal timescale appears to be set in such models by a combination of gyres adjustment times and the time taken by upper-ocean heat content anomalies to complete one circuit in the gyre. In at least one coupled ocean-atmosphere GCM experiment, however, such internally-generated decadal climate variability is overpowered when external radiative forcing at multidecadal timescales is imposed on the model climate system.

While it is believed that there may be a coupled ocean-atmosphere mode, oscillating at decadal timescales, in the tropical Atlantic, analyses of observations and some coupled ocean-atmosphere GCM experiments show that such variability is generated in the tropical Atlantic due to a combination of the atmosphere forcing the ocean locally and upper-ocean heat content anomalies coming into the tropical Atlantic from the extratropical Atlantic along the eastern boundaries of the basin, perhaps in the subtropical gyres or in shallow, wind-driven meridional circulations. Based on some observations that sea level pressure variations over the North Atlantic, as indicated by the NAO, are correlated with the tropical South Atlantic decadal SST variations, a mechanism has been proposed whereby high-latitude climate fluctuations in the North Atlantic can affect the tropical Atlantic. In this mechanism, variations in atmospheric circulation (as reflected by fluctuations in the NAO) affect the rate of deep convection in the Labrador Sea, and thus influence the thermohaline circulation and the cross-equatorial heat transport, thereby influencing tropical Atlantic SSTs. Thus, it appears that decadal variations in the tropical South Atlantic SSTs, sea level pressure variations over the North Atlantic, deep convection rate in the Labrador Sea, and cross-equatorial heat transport in the tropical Atlantic may be components of a meridional teleconnection pattern varying at decadal timescales. It is, of course, an open question whether the tropical South Atlantic SST variations are caused by feedbacks through this 'loop' or by some other processes local to the South Atlantic region.

There are several processes which appear to play an important role in influencing variability of the MOC on a variety of timescales.

(a) The intensity of the MOC is linked to the transfer of heat from ocean to the atmosphere over the high latitudes of the North Atlantic. This process is an effective buoyancy flux, and helps to create the dense water necessary to drive the MOC. Observational analyses have clearly shown that the atmospheric circulation over the North Atlantic plays a critical role in determining these heat fluxes, largely through altering thenear-surface wind speed and the air-sea gradients of temperature and moisture. A positive phase of the NAO is linked to enhanced ocean to atmosphere heat flux. Thus, fluctuations in the NAO are a prime candidate for generating variability of the MOC. In addition to affecting the heat fluxes, the associated Ekman transport alters the meridional fresh-water transport.

(b) Enhanced oceanic convection is hypothesized to enhance the MOC. Thus, the stratification of the water column is an important influence on the MOC. Variations in the fresh-water budget at high latitudes can create variability in the MOC. In particular, fluctuations in the export of fresh water and sea ice from the Arctic can have a profound affect on the MOC. Some work has suggested that the Great Salinity Anomaly of the 1970s resulted from an enhancement of the fresh water export from the Arctic which suprressed oceanic convection (and thus possibly the MOC).

(c) The wind stress at the southern boundary of the Atlantic Ocean has been hypothesized to play a role in the maintenance and variability of the MOC by altering the inflow of water to the Atlantic basin. Some numerical modeling studies support this hypothesis.

Multidecadal SST changes in the North Atlantic have been found to occur in several coupled ocean-atmosphere GCMs. Experiments with the GFDL ocean model show, however, that multidecadal variability of the North Atlantic thermohaline circulation could be excited by temporally-stochastic surface flux forcing on the ocean. Observations suggest that the 50-70 years climate variability may be forced by solar irradiance variability phase-locked to this internal mode of variability of the North Atlantic thermohaline circulation. SSTs in the GISS coupled ocean-atmosphere GCM show a response to multidecadal-century scale changes in solar irradiance, with the solar forcing enhanced by a greater amount of atmospheric water vapor, less cloudiness, and less sea ice.

So, it appears that the primary mechanism of decadal-multidecadal SST and upper-ocean heat content variability in global coupled ocean-atmosphere or ocean-only models is the response of the ocean to atmospheric forcing, either the integration of forcing with temporally-stochastic characteristics or instantaneous response to quasi-periodic forcing. The association of decadal SST and upper-ocean heat content anomalies with ocean gyres is quite clear in some of these models, as is the association of multidecadal anomalies with the thermohaline circulation.

3 - DATA REQUIREMENTS

From the analyses of observations and model experiments, it appears that the rectification of multifrequency atmospheric forcing by the upper oceans, subtropical and subpolar ocean gyres in the Atlantic and Pacific Oceans, and thermohaline circulation in the Atlantic Ocean play major roles in multiyear to decadal climate variability. Extratropical Rossby waves and coastal Kelvin waves also appear to be important. As mentioned earlier, for climate variability, SST is the most important quantity that is influenced by oceanic processes. The most important quantities and other requirements are listed in tables 1 and 2.

Which data do we need to understand the phenomenons described above?

- SST, surface stress, upper-ocean heat content, surface salinity
- Subtropical gyres
    - Coarse horizontal resolution, vertical profiles of temperatures, velocities, and salinity in the first 500 meters of the tropical-subtropical segments of subtropical gyres in the Atlantic, Pacific, and Indian Oceans
- Meridional overturning circulations
    - Geochemical tracers to measure tropical-subtropical water masses

- Large-scale dynamic topography to estimate geostrophic currents and heat transports
- Freshwater flux (sea ice thickness and concentration, P-E, river run-off) in the North Atlantic
- Atmospheric forcings as a proxy for meridional overturning in the North Atlantic
- Remote sensing of bottom pressure through satellite gravimetry to estimate bottom currents that are a part of the large-scale THC

Are the data we need to study dec-cen variabilty the same as those to study global warming?

- Yes, the major oceanographic impact of global warming is supposed to be on the THC. So, we need to measure THC-related variables for studies of both.

Which data are most useful for decadal prediction?

- SST, upper-ocean temperatures and salinities

What is the role of data assimilation in understanding and predicting dec-cen and anthropogenic climate phenomenon?

- To provide dynamically-consistent ocean data sets for scientific analysis, and predictability and prediction studies. This is very important as long as the observing system is sparse.

Are accurate surface flux measurements needed?

- Yes. To force ocean models and to estimate the THC.

Are the fluxes produced by operational NWP centers adequate? Do we need any changes in the meteorological observing system?

- The fluxes are not adequate, as has been shown by ocean model integrations.

Climate phenomenon	Ocean phenomenon	Variables
2.1 Global scale decadal-multidecadal climate variations	Subtropical and subpolar gyres; Rossby waves	SST, surface stress, upper-ocean heat content, surface salinity
2.2 Decadal and longer timescale variations in interannual ENSO characteristics	Pacific and Indian "warm pool"; tropical-subtropical Pacific thermocline; tropical-subtropical meridional circulations	SST, surface stress, upper-ocean heat content, thermocline depth
2.3 Decadal-multidecadal variations in the Pacific climate	Subtropical and subpolar gyres; Rossby waves; coastal Kelvin waves	SST, surface stress, upper-ocean heat content
2.4 Decadal variations in tropical-subtropical Atlantic climate	Subtropical gyres; tropical-subtropical meridional circulations; Rossby waves; coastal Kelvin waves	SST, surface stress, upper-ocean heat content
2.5 Multiyear to decadal timescale NAO-AO-sea ice variations in the North Atlantic	Subtropical and subpolar gyres; thermohaline circulation; Rossby waves	SST, surface stress, upper-ocean heat content
2.6 Multidecadal-centennial timescale variations in the meridionally overturning circulation	Convection	SST, surface stress, upper-ocean heat content

Table 1. Observational requirements for climate phenomena.

How will an ocean observing system help?

- A basin-scale ocean observing system, permanently in place, can foretell surface and subsurface oceanic heat and circulation anomalies that have the potential to influence climate over land areas at multiyear-decadal timescales.

- A global view of ocean observations; permanence and continuity of data streams; accuracy and stability of instruments and techniques.

In view of the basin-scale nature of the processes, likely similarity of processees associated with gyre circulations in the various ocean basins, and the likely direct and indirect (via the atmosphere) interactions among ocean basins at multiyear to decadal timescales, it would be highly synergistic and cost-effective to take a global view of ocean observations when designing and implementing an ocean observing system for multiyear to decadal timescale climate variability.

Because of the intrinsically long-term nature of these phenomenons, the observing system must be designed to return data continuously and must be in place in some form permanently. The permanence should be attached to the variables needed to be observed and not to the technology put in place. These requirements impose stringent constraints on the accuracy and stability of measuring instruments, and the long-term commitment of resources. The ocean observing system for multiyear to decadal timescale climate variability studies should be flexible enough to accommodate improvements in measuring technology and techniques.

Development of new technologies and systems to meet challenges; data management and dissemination
Synergistic deployment of satellite-based sensors, satellites for data relay, and in-situ data
Development of data assimilation systems as an integral component of the decadal-centennial ocean observing system

4 - CHALLENGES

The data requirements for an ocean-observing system to study decadal-to-centennial scale climate variability, outlined in the previous section, pose numerous challenges. These challenges range from implementing a concept for such a system to developing new technologies. Specifically, these challenges are,

- to think, plan, and implement an ocean observing system on multidecades-century timescale and 'global' space scales;
- to design observing systems that are flexible enough to incorporate 'course correction';
- a minimum observing system must be in place permanently, and has to be refurbished and maintained indefinitely;
- satellite orbits that do not drift, injection into the correct orbit, maintenance of precise orbits, refined algorithms to maintain consistent time series from one satellite sensor to the next, on-board redundant calibration, stated specifications for instrument stability, dedicated in-situ calibration/validation sites determined on an instrument-by-instrument basis;
- continuity of calibration of in-situ sensors;
- difficulty of anchoring moorings in regions where there are strong currents; and
- data management and dissemination.

5 - PRIORITIES

- Continuing global measurements and assimilation of SST, surface stress, dynamic topography (upper-ocean heat content), sea ice, atmospheric forcings

- Monitoring system for vertical profiles in the tropical-subtropical segments of the subtropical ocean gyres

- Freshwater flux (rainfall, evaporation, river run-off, sea ice) and surface salinity

- Geochemical tracers to monitor movements of tropical-subtropical water masses

- Remote-sensing of bottom pressure through satellite gravimetry

- Remote-sensing of mixed-layer thickness

6 - CONCLUDING REMARKS

In view of the basin-scale nature of the processes, likely similarity of processees associated with gyre circulations in the various ocean basins, and the likely direct and indirect (via the atmosphere) interactions among ocean basins at multiyear to decadal timescales, it would be highly synergistic and cost-effective to take a global view of ocean observations when designing and implementing an ocean observing system for multiyear to decadal timescale climate variability. Because of the intrinsically long-term nature of these phenomenons, the observing system must be designed to return data continuously and must be in place in some form permanently. The permanence should be attached to the variables needed to be observed and not to the technology put in place. These requirements impose stringent constraints on the accuracy and stability of measuring instruments, and the long-term commitment of resources. The ocean observing system for multiyear to decadal timescale climate variability studies should be flexible enough to accommodate improvements in measuring technology and techniques.

An ocean data assimilation system should be an integral part of the ocean observing system for decadal-centennial timescales. Only model-assimilated data can provide dynamically-consistent ocean data sets for scientific analysis, and predictability and prediction studies. This is very important as long as the observing system is sparse, which is likely to be the case for the foreseeable future. In spite of the problem and challenges outlined here, it is clear that a basin-scale ocean observing system, permanently in place, can be very useful in foretelling surface and subsurface oceanic heat and circulation anomalies that have the potential to influence climate over land areas at multiyear-decadal timescales.