Statement to the
US Commission on Ocean Policy

Understanding the Ocean's Role in Climate

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Introduction

This statement summarizes the present understanding of the roles of the oceans in climate, including the oceanic impacts of climate variability and change. Areas where additional research is required are identified. Issues that are of particular relevance for the Pacific Region are noted. The programmatic context for US ocean climate research is considered. Recommendations are made to:

- Enhance sustained ocean observations,
- Enhance ocean process research to improve numerical models for ocean-state estimation and forecasting, and
- Develop mechanisms to improve both inter-agency and inter-program cooperation and coordination in ocean climate research

The Ocean's Role in Climate

Because of its huge heat capacity and carbon reservoir, the ocean plays a central role in the Earth's climate system. The essential climate-related characteristics of the ocean are that

- it stores and releases large quantities of heat, freshwater and soluble gases,
- heat, freshwater and gas releases are sometimes substantially separated in space and time from their point of storage, due to ocean dynamics and mixing
- freshwater and gas fluxes are determined partly by direct and indirect effects of ocean surface temperatures
- carbon fluxes, storage and natural sequestration depend on highly complex biogeochemistry and marine ecosystems dynamics

These characteristics include the integrating (buffering) effect of the ocean, which emphasizes low frequency variations of heat and carbon and delays these signals in time. They also include remote forcing and delays due to slow internal wave propagation and slow transport by currents. Such lags are important for switching the signs of ocean temperature anomalies and for developing coupled oscillations.

The Earth's climate varies because forcings vary, and also because unstable coupled ocean-atmosphere modes exist. The most prominent such forcing is the variable solar radiation due to orbital mechanics of the Sun and Earth, which include the annual cycle and the very long Milankovitch cycles. Another forcing is associated with human modification of the concentrations of radiatively active trace gases and aerosols in the atmosphere.

Internal modes of climate variability exist due to unstable resonances between atmosphere and ocean. The ocean integrates atmospheric forcing which tends to emphasize low frequency surface temperature variability. In certain areas, low frequency variations of sea surface temperature feed back onto surface winds in a positive sense, leading to unstable modes of climate variability that exist solely because of this strong coupling of the ocean and atmosphere. The El Niño/Southern Oscillation (ENSO) is the dominant mode, occurring at intervals of 3-5 years, with its locus in the equatorial Pacific but with global impacts. On the time scale of decades, several modes have been identified, such as the Pacific Decadal Oscillation (PDO; Mantua et al., 1997), the North Atlantic Oscillation, and the Tropical Atlantic Variability. It is not yet clear to what extent these are really distinct modes, but it is certain that they interact (Marshall et al., 2001). Even the annual cycle, though forced by the orbit of Earth around the Sun, is modified by coupled ocean-atmosphere interactions.

As indicated by the discussion above, scientists have tended to address climate variability in the frequency domain because some variations, such as ENSO, show relatively narrow-band oscillatory behavior, and because this tends to simplify the problem. While this has allowed progress, pervasive implicit assumptions about the linearity of climate variability now hold us back. The existence and character of ENSO in numerical models depends on the background state of the tropical Pacific Ocean, which varies over decades. The skill of model ENSO hindcasts and predictions varies on decadal time scales. This may be due to nonlinear interaction with the PDO in ways that are not clear, although several hypotheses have been developed (Lukas et al., 1999). In fact, nonlinear processes in the ocean and in the coupling of the ocean with the atmosphere are very important, making assumptions about time- and space-scale separability potentially misleading. Nonlinear ocean processes may lead to rectification of high frequency variability into low frequencies, while low frequency variations are observed to modulate high frequencies. Trends and threshold effects can lead to sudden changes that require time domain rather than frequency domain description. Even though ocean general circulation models operate in the time domain and include some essential nonlinearity, linearizing assumptions have greatly influenced the parameterization of subgrid-scale processes in these models.

Because the anomalies associated with ENSO are relatively large, modulation of other ocean phenomena on many time and space scales takes place. ENSO has a strong direct influence on mixing and stratification variations observed in the Hawaii Ocean Time-series, and thus also on nutrients and biology (Karl et al., 1995; Karl 1999). There are strong signs as well of decadal variations in mixing, circulation and biogeochemistry, with the appearance of a fundamental reorganization of the ecosystem. These observations have provided great insights into the functioning of the large subtropical gyre of the Pacific Ocean, challenging some of the most closely held assumptions in ocean biogeochemistry and providing clues to the mechanisms through which ocean biology may influence global climate. The most significant biogeochemical features are: (1) the variations in the mechanisms of nutrient supply, especially the ecological consequences of “pulsed” nutrient delivery, and the nutrification of low-latitude regions in the absence of turbulence (e.g., enhanced N_2 fixation [Karl et al., 1997; Karl, 1999]), (2) the relationships between ocean physics and ocean biology, especially for community structure and trophic dynamics (Cullen et al., 2000), and (3) the resultant physical and biological controls on the ocean’s carbon pump. The decoupling of production, export and remineralization processes in time and space, and the detection of decade-scale, climate-driven ecosystem perturbations and feedbacks combine to reveal a time-varying, biogeochemical complexity that is just now becoming evident in ocean time-series data sets.

Recent observations and previous modeling studies all suggest that eddies play a much more important role in determining large-scale ocean circulation and biological productivity than previously estimated (e.g. McGillicuddy et al., 1998). However, the physical mechanisms responsible for these eddy-induced effects are not well understood, mostly because of the lack of high-resolution ocean observations. The recent discovery near Hawaii of a submesoscale eddy that carried undiluted waters from Baja California has underscored the oversimplifications involved in the traditional use of linear advective-diffusive models with simple eddy parameterizations. Such eddy generation is strongly affected by the large amplitude coastal Kelvin waves during the occurrence of El Nino events (Lukas and Santiago-Mandujano, 2001; Zamudio et al., 2001) thus influencing slow variations in the heat budget of the northeastern Pacific (Roemmich and Gilson, 2001) in addition to net counter-gradient property transport. The propagation of these eddies is also affected by the Rossby waves that radiate westward from the Mexican coast; eddies tend to take a more northwestward path into the interior of the subtropical gyre following El Niño events. Because mesoscale eddies modify upper ocean processes in ways that tend to enhance biological productivity, the possibility is raised that ecosystem changes north of Hawaii may also be due to remote and rather indirect ENSO forcing. Coupled physical climate models do not yet explicitly include mesoscale eddies. It will take considerable research (and still greater computational power) to include the potentially important interactions of ecosystems with climate in these improved physical models.

Another example of strong nonlinearity is associated with the generation of internal tides at particular topographic features (such as the Hawaiian Islands) and their subsequent breaking, generating strong vertical mixing. Such mixing is highly variable in space and time, unlike the parameterizations of vertical mixing in coarse-grid ocean general circulation models. While these effects may not directly influence climate, they are important for the distribution and magnitude of nutrient fluxes and thus likely influence ecosystems.

Finally, a nonlinear threshold effect may be important in the interaction of deep ocean convection in the North Atlantic with varying surface freshwater fluxes leads to the so-called thermohaline catastrophe discovered in numerical ocean models. This occurs when the deep meridional overturning circulation of the Atlantic shuts down suddenly, with profound impacts on surface temperature. Evidence of abrupt climate changes has been discovered in paleooceanographic records, and it is suggested that such physics is involved (NRC, 2001).

Oceanic Impacts of Climate Variability and Change

Climate variability and change affect ocean temperatures, salinity, density stratification (and thus mixing), sea level, currents, and surface wave statistics. These all affect various ocean resources and human activities, motivating national investments in climate research. Hawaii, Samoa, and US Affiliated Pacific Islands sit within the core of the ENSO phenomenon, feeling its effects fully. Pacific islands and their populations are particularly vulnerable to climate variability and change. The statement by Dr. Nancy Lewis to the Commission addresses these vulnerabilities. Providing useful information about ocean climate variations to anticipate impacts is also an important objective of the research devoted to understanding the ocean's role in climate. This is discussed below.

Fisheries are strongly affected by changes in ocean thermal structure; the original research efforts on El Niño were aimed at understanding eastern equatorial Pacific tuna catch variations. In recent years, we've learned that the tuna fishery of the western tropical Pacific is displaced eastward during El Nino events (Lehodey et al., 1997), and that the salmon fishery of the Pacific Northwest is affected by the PDO (Mantua et al., 1997). The phenomenon known as coral bleaching occurs when tropical coastal waters warm by as little 1°C above the typical range. Such episodes seem to have occurred more frequently in the recent decade. The Great Barrier Reef of northern Australia is the latest to undergo a bleaching episode associated with recent warming in the western Pacific. While the proximate cause is ENSO-related surface temperature increase, this appears on top of a longer term trend to warmer surface temperatures in the western Pacific warm pool.

Climate variations include surface wind stress changes, leading to cycles and trends in ocean currents and wave statistics. These greatly affect navigation around and between islands, as well as affecting the beaches and reefs upon which these waves ultimately break. Ocean currents affect fisheries directly through lateral displacements and larval dispersion, and indirectly through the influence of upwelling on primary productivity.

While global warming is expected to cause significant sea level rise in many places, depending on the corresponding wind and current changes there may be sea level drops in some locations. Significant sea level changes are also due to El Niño, decadal climate variability and to geological variations. For example, during El Niño events, coral reefs in the western Pacific have been damaged due to excessive exposure during exceptionally low tides. Nonlinearities again appear to be important in a very practical setting. The slow rise of sea level associated with global warming provides the background state upon which short term events, such as hurricane storm surge and extreme wave setup, cause sudden inundation of the coastal zone and extreme erosion events. Combined with the possibility of more intense and/or more frequent ENSO events associated with global warming (suggested by some climate models), the prediction of inundation and erosion is quite complicated.

To address ocean climate impacts, ocean state assessments and predictions of subsequent ocean evolution are needed. These however depend on still relatively crude (but improving) numerical models. To produce sufficiently accurate assessments, a critical mass of observations is required. What constitutes a "critical mass" depends on the quality of the numerical representation of numerous natural processes, the quality of the surface boundary forcing for the model, and the particular application. Assessment and even prediction of ENSO temperature and sea level anomalies is less challenging than estimating the present circulation of the tropical ocean.

Nested data assimilation methods are required to support downscaling of basin-scale ocean analyses to island coasts. Some progress has been made on the problem of interfacing high-resolution physical models of continental margins with coarser resolution basin-scale models, and performing dynamical analyses of multivariate observations (e.g., Haidvogel et al., 2000; Walstad and McGillicuddy, 2000). However relatively little work has been done on the problem of island coasts, where steep topography is the rule, and where coral reefs complicate the problem further. Detailed coral reef circulation models are important foundations upon which to base ecosystem models (e.g. Wolanski et al., 1989), but providing the appropriate open ocean boundary conditions remains an important problem.

Impediments to Better Understanding and Applications

A number of factors impede progress in achieving the desired levels of understanding of ocean climate variability and progress on improved application of that understanding. These include observational infrastructure limitations, scientific challenges, and programmatic weakness.

Inadequate numbers of long multivariate time series

It is impossible to effectively study ocean climate variability on time scales that are longer than have been observed. Ocean models can of course generate any length of time series, but they are of little value unless they reproduce the essential characteristics of nature. It is obvious that without long records of natural variability, we will never know how well our models work. Our longest time series are of surface temperature and sea level, exceeding 100 years at a few coastal observing sites. In a very few locations, such as Station P in the North Pacific and Station M in the North Atlantic, subsurface temperature and salinity measurements were made for more than a decade, but most of these have been discontinued. The exceptional time-series observations of subsurface temperature, salinity and oxygen at Station S off Bermuda now span 50 years. Only the time-series stations off Hawaii (HOT) and Bermuda (BATS), initiated under the auspices of the JGOFS program, have both comprehensive physical measurements and biogeochemical measurements over the water column for more than a decade (Karl et al., 2001). It is crucial to maintain these long time-series and to initiate new sites for time-series (Send et al., 2001). Collaboration among the CLIVAR (Climate Variability and Predictability Program), the Carbon Cycle Science program, SOLAS (Surface Ocean – Lower Atmosphere Study) and the Integrated Ocean Observing System (IOOS) programs is required.

Ignorance of connections between spatial structures and temporal variability

The space-time structure of variability has to be known well for parameterizing processes not resolved in numerical models, for the design of long-term observing systems and for ocean data assimilation procedures to be successfully implemented. This requires deliberate oversampling, which has rarely been done in the ocean for physical variables, and never approached for biogeochemical variables.

The ENSO observing system represents the most comprehensive and systematic set of observations of any region of the open ocean, yet is has not oversampled all significant variability. It includes the trans-Pacific TAO array of near-equatorial moorings, which was built up during the 10-year long TOGA program to observer and improve understanding of ENSO and to support numerical predictions. While the key thermal structure variations are observed (in conjunction with satellite altimeters), important meteorological, salinity and current variability has not been adequately observed. With the QuikSCAT satellite, the important surface wind forcing structures are resolved, but air-sea heat and moisture fluxes, as well as salinity and velocity structures, are inadequately observed. The Argo array of profiling floats will help address the need for salinity observations, once it is fully implemented. But the relatively small time and space scales of near-surface salinity variability require denser observations, or integrating observations such as would be provided by the Aquarius surface salinity satellite.

Outside of the Pacific tropics, the impacts of ENSO variability are considerably more subtle (away from coastal regions), though still very important for ecosystems. In the midlatitude ocean, decadal variability is at least as large as the ENSO signals, and both must be adequately observed. As the time scale of ocean climate variability increases, slow and relatively subtle ocean processes become more important, placing greater demands on the observing system. For example, the physical oceanographic community struggles to develop cost-effective strategies for observing the variability of the Atlantic meridional overturning circulation, in the presence of eddies that may contain as much signal as noise.

Major new *in situ* observing initiatives are underway to: measure global temperature and salinity profiles in the upper 2000 m every 10 days using profiling floats (ARGO, 1999; Roemmich and Owens, 2000); to implement a sparse global network of moored buoys to measure air-sea interaction parameters and subsurface temperature, salinity, velocity and biogeochemical properties (GEO, 1999; Send et al., 2001); and a network of seafloor observatories (NRC, 2000) measuring a broad array of variables. Common to all of these planned efforts is the concept of real-time data return in support of applications. With the complementary coverage provided by satellite estimates of sea level, surface wind, sea surface temperature and ocean color the Global Ocean Data Assimilation Experiment (GODAE, 1999) planned for 2003-2007 aims to capitalize on this global data coverage to demonstrate the utility of routine global ocean state analyses. The GODAE effort will likely be extended in some form, supporting, and being supported by, the developing Integrated Ocean Observing System (IOOS; NORLC, 1999).

There are a number of limitations to what GODAE will do. It will not provide the required multidisciplinary (including biology and chemistry) perspectives on ocean observations. GODAE will focus on global analyses, while regional analyses will depend on regional observing system enhancements and sophisticated data assimilation approaches to deal especially with downscaling into the coastal environment where many of the applications will likely be centered. This downscaling will challenge data assimilation efforts to bridge the deep open ocean with the coastal environment, where topographic effects are so important.

Successful design and implementation of extra-tropical ocean observing systems, and derivation of useful ocean climate products, requires a collaboration among the CLIVAR, IOOS, GODAE, and SOLAS programs

Ignorance of marine ecosystems dynamics and inability to observe key elements

Determining the mechanisms, natural pathways and rates of carbon storage and sequestration in the ocean is crucial to building accurate models of climate change (Carbon and Climate Working Group, 1999; Doney and Glover, 2001). This requires greatly improved understanding of the factors that govern variability of marine ecosystems, and that requires substantial investment in new observations. A critically important task is to successfully integrate expanded observations of time-series at key locations, observations of atmosphere-ocean exchange of biologically important compounds (such as iron in dust), periodic global ocean surveys, remote sensing of the oceans, large-scale airborne measurements over the oceans, and atmospheric data from island stations. The conceptual framework for interpreting these observations must be developed and tested during strategically planned intensive regional *in situ* experiments. This requires enhanced cooperation and coordination across disciplines and across research programs. The GLOBEC program has been addressing physical influences on higher trophic levels while work on primary production took place under the recently completed JGOFS program. The new US Carbon Cycle Science program is intended to take a more comprehensive view. Effective collaboration with CLIVAR and SOLAS is important.

Gaps between research programs

Major international and national research programs aimed at understanding particular aspects of ocean climate variability are all underfunded. This virtually guarantees that scientific areas of natural collaboration between and among programs will not happen, as scientific leadership tends to descope programs to fit anticipated budgets by concentrating within the smallest number of scientific disciplines consistent with selected program objectives. This has happened, for example, with the US CLIVAR and SOLAS programs: CLIVAR backed away from air-sea interaction involving chemistry, while SOLAS has backed away from the physics challenges limiting understanding of air-sea chemical fluxes. Collaboration across disciplines is limited by budgetary constraints, and by the "reward" systems for research scientists.

Logistics and political barriers

The Pacific Ocean is huge, and long transits are required for research vessels working on basin-scale problems. Some regions important to observe are outside of national EEZs, presenting a less obvious imperative for maintenance of observations in these regions. Some important regions are within national EEZs where key observations cannot be made, either for financial or political reasons. International cooperation is clearly required to support effective research towards understanding the ocean's role in climate and for the practical application of that knowledge.

Summary and Recommendations

The simplest ocean climate problems have been tackled with substantial success. Now, the very challenging ocean climate problems that remain involve strongly nonlinear processes. The successful TOGA and WOCE research programs showed the value of finding an appropriate balance between observations, numerical modeling, and process studies for making progress in understanding ocean climate variability. For ocean climate assessment and prediction purposes, the triad of observations, data assimilation, and numerical prediction is essential. To regain a balance in ocean climate research now that modeling and data assimilation have advanced significantly, new sustained ocean observations and new intensive (but limited-duration) observations are needed.

Ocean observations: Build on the evolutionary TOGA model

Building on the ENSO observing system, and the successes of WOCE, additional sustained ocean observations are needed for better understanding and for improving numerical models of the roles of ocean processes in the Earth's climate system. These observations are essential to constrain model-based climate and ocean-state assessments and predictions. Existing ocean remote sensing capabilities must be maintained, if not augmented. The Argo array of profiling floats must be fully implemented and maintained. Highly interdisciplinary Eulerian observatories are required to complement these broad scale observations, to gain understanding of nonlinear interactions on relatively small space and time scales and their roles in ocean climate variability.

Data assimilation and Modeling: Work the interface between coasts and blue water, and between physics and biogeochemistry

Focused research on ocean data assimilation is required to make best use of new observations, and to help guide additional observational investments. This research requires the intensive space-time nested field measurements as part of process experiments, which benefit from the context that can only be provided by data assimilation. Special attention must be paid to observing, understanding and modeling the interaction between the coastal environment and the deep ocean, both to provide improved boundary conditions for coastal assessment and forecasts, and to improve boundary conditions in basin-scale assessments and forecasts. Special attention must also be paid to the impacts of small-scale physics on biogeochemistry. Ocean observatories can play a key role in studying the critical interactions, in a multi-disciplinary framework.

Inter-program and Inter-agency coordination/cooperation: Increase funding, target gaps

Climate-related research programs involving the ocean need greater support, both in terms of funding and in terms of infrastructure and management. Presently, the US supports programs such as CLIVAR, GLOBEC, SOLAS, and Carbon Cycle Science, all within the framework of the USGCRP. These individual programs suffer from insufficient inter-agency cooperation and coordination. The scientific communities involved in these programs also do not cooperate very well because of competition for resources. Budgetary fears result in the natural intersections of such programs being under-funded, even when a single discipline is involved. Such budgetary fears provide substantial barriers to interdisciplinary research.

A programmatic mechanism for fertilizing such natural areas for inter-program and interdisciplinary collaboration is needed to focus reasonable levels of effort on these (ultimately critical) gaps. An example of success is the cooperation of CLIVAR and Carbon Cycle Science researchers in developing a shared plan for reoccupying selected WOCE hydrographic sections. A counterexample is the gap that is developing between CLIVAR and SOLAS on research needed to improve understanding of the physics of air-sea interaction both for physical climate purposes and for chemical exchanges between atmosphere and ocean. The National Ocean Partnership Program (NOPP) could provide the framework to address such gaps.

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