Ocean, Ice, and Climate: The Slow Dance of a Complex System

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ABSTRACT - **The time horizon of global change is on scales of years, decades, centuries, and beyond, and this variability can have tremendous regional impact. The importance of the oceans and cryosphere in climate change increases with time scale because of their large thermal inertia. Over the past few years, NASA's Earth Science Enterprise has developed a research strategy to address climate relevant questions about the ocean and cryosphere, such as: How is the global ocean circulation varying on interannual, decadal, and longer time scales?; and What changes are occurring in the mass of the Earth's ice cover? This strategy starts with basic exploration utilizing satellite measurements, leads to improved understanding by incorporating data and models, and ends with improved prediction and benefit for the future. In this paper we consider the science and technology challenges for the ocean and cyrosphere strategy over the next twenty-five years.**

INTRODUCTION

In 1611 Commander Hendrik Brouwer of the Dutch East India Company made a courageous decision. While rounding the Cape of Good Hope on his way to Batavia (now Jakarta), he chose to sail an unknown course eastward with the prevailing winds and ocean currents. The normal route was north along the coast of Africa and then east to India with the southwest monsoon. Instead, he sailed due east for 4000 miles and then turned north. He arrived in the East Indies in half the usual time of 18 months [1]! Knowledge of the ocean's state, has long been of interest to commercial shipping, fishing and military operations. While of critical importance to these specialized endeavors, the ocean and cryosphere remained, for the most part, a remote interest that was not thought to effect most of society*

Recently, there has been increased public awareness of the role of the oceans and cryosphere in the longer term states of the atmosphere. Much of this attention is directly the result of the dramatic effects of the recent El Niño and La Niña on global seasonal weather trends and tropical storm formation.

The focus on ocean and ice contributions to weather trends has heightened interest in a variety of ocean and ice variability, such as the modulation of ENSO by the Pacific Decadal Oscillation, rising sea level caused changes in glacial cover, and absorption of anthropogenic carbon dioxide from the atmosphere into the ocean. Such processes are of obvious importance in understanding and predicting long term changes in the global climate system.

THE COUPLED SYSTEM

Predicting global change and its impacts on the environment and economy depends on understanding coupled physical processes and feedbacks between the components of the Earth system on many timescales. The ocean and cryosphere are the most important components of the system on longer timescales because of their relatively large thermal inertia. The complex nonlinear processes that ultimately determine the evolution of the climate system means that the ability to predict changes depends on the accurate representation of those processes and couplings in computer models.

Present day numerical models are limited in their ability to simulate the spectrum of climate variability on a global scale. These conditions are due in part to discretization errors imposed

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* In 1616, Dirck Hartog in his ship the *Eendracht* followed Brouwer's route and discovered the west coast of Australia.[1]

by computational limitations. Over the next 25 years these errors should be reduced with advances in information technology. Errors remain in the representation of small-scale physical processes such as mixing, diffusion, convection, radiation, and air-sea coupling. They need considerable attention through process studies and numerical experimentation.

Prediction skill also depends on the accuracy of initial states of the system. The accuracy required for initial states depend on the time scale of interest (seasonal, interannual, decadal, and centennial). This is and will remain an area of highly active research.

DATA ASSIMILATION

The assimilation of atmospheric observations into global numerical weather prediction models has played a key role in identifying deficiencies in atmospheric models for weather time scales. Similarly, the confrontation between ocean data and ocean models has begun to help with model validation and improvements.

The challenges of ocean data assimilation are significant. The energetic scales in the ocean need to be resolved to reduce the biases in models. With a reduction in biases, the assimilation procedure can make most effective use of the observations in estimates of the ocean state and in prediction of future states. Thus, the computational requirements are high.

The paucity of ocean observations makes the validation of models and assimilation systems problematic. This problem is partly relieved by the availability of extensive satellite observations of the ocean surface.

The challenge for assimilation systems and models is to extrapolate the surface information into the subsurface ocean. These issues will begin to be addressed through the coordinated Global Ocean Data Assimilation Experiment (GODAE) and the associated global array of profiling floats (Argo). Argo will help validate the assimilation system's capabilities to gain useful subsurface information from satellite observations. GODAE (2003-2007) will be a demonstration of the practicality of global ocean data assimilation. It is only the beginning of a concerted effort at routine ocean product generation that will play a central role in the definition of the observing system needed for ocean climate analyses and prediction.

OCEAN OBSERVATIONS

A sustained ocean observing system must take into account the need for continuity, as well as the desire to improve the observing system and make it more cost-effective. Ocean data assimilation and coupled model prediction skill provide the context for ensuring continuity and assessing the utility of various data streams.

The utility of particular data streams includes the need for data continuity during the assessment. It is known that there are phenomena that occur on a variety of time scales in the oceans and cryosphere that interact with each other. The Pacific Ocean, for example, underwent changes in its background state in 1976 and the early 1990's. Computer models that seemed to work well with simulating and even predicting Los Niños in the 1980's performed very poorly for the events of the 1990's. No model predicted the large magnitude of the El Niño that occurred in the late 1990's. Only with long term consistent measurements of key parameters can the full dynamics of complex interactive processes that govern events like El Niño begin to be understood. Those key parameters can only be identified through careful and accurate computer simulation/assimilation and then validation of those simulations with observations.

Continuity. The plan for continuity of ocean observations from space is in its infancy. Time series of surface height, winds, temperature, color, and sea ice are being extended into the twenty first century. By 2010 nearly three decades of observations may be available for sea ice and sea surface temperature, whereas, more than a decade will be available for the other variables. The continuation of these data to 2025 will technology development to reduce cost, better accuracy, and increase longevity. Technology challenges for resolution and continuity include: interferrometry, large antennae, and small lightweight radars for sea surface topography; large microwave antenna for SST and sea ice; and steerable radiometer systems for surface winds.

New Measurements. Ocean estimation is exacerbated by the importance of surface forcing by atmospheric winds, heat fluxes and water fluxes. Measurements of the ocean surface that give information on the temperature, salinity, depth of the mixed layer, and vertical mixing properties, as well as the forcing fields themselves will be critical in assessing and improving the representation of air-sea coupling in numerical models.

In the next decade improvements in SST will use passive microwave techniques. In addition, geostationary, microwave, and infrared data will be combined to produce high spatial/temporal resolution SST as part of GODAE. In the Europe and the US development of microwave techniques to measure salinity are underway and may lead to space flight in this decade. Technology improvement is needed in large antenna structures and more accurate radiometers to address the higher resolution requirements for SST and SSS in the next twenty-five years. Research with laser technology to investigate upper ocean mixing needs to be explored.

Air-sea fluxes will be addressed with surface winds, water vapor, and rainfall measurements in the next decade. Use of formation flying may occur in this decade to improve temporal resolution and provide coincident measurements by multiple sensors. Technology improvements needed are lightweight, economical, radar and radiometers to address resolution concerns. The challenge for sea ice is to measure its thickness, as sea ice modulates the energy exchanges between the ocean and atmosphere and directly influences the thermohaline circulation through brine rejection. ESA's Cryosat mission (2003) will explore radar technology for this observation, while NASA's ICESaT (2001) mission will utilize laser technology towards the same end.

ICE SHEETS

Understanding the rate and character of sea level rise is important to national and international economics and policy. While the estimated rate of sea level rise over the last one hundred years has been on the order of 2 mm/yr [2], there is evidence that in the past, sea level has risen abruptly by as much as 50 mm per year [3]. A rapid rise can result from enhanced discharge from the Greenland and Antarctic ice sheets, which contain enough ice to raise sea level approximately 70 m [4]. The smaller ice caps and glaciers, though limited in size, are also important in the near-term, as they are sensitive to small climate perturbations, contributing about one quarter of the current sea level rise [2]. Assessing the mass balance of the ice sheets, ice caps, and glaciers and understanding the mechanisms that control this balance is a fundamental component of the NASA Earth Science Enterprise research strategy with primary focus on ice sheets.

Combinations of active and passive satellite sensors operating at various frequencies and polarizations provide new perspectives on ice sheet behavior and a wealth of new information. Radar altimetry identified areas of mass loss and mass gain on the Greenland and Antarctic ice sheets [5,6]. Recent advances in synthetic aperture radar intereferometry provide valuable information on ice sheet dynamics and grounding line behavior [7]. When combined with ancillary data, these measurements yield estimates of mass balance for various outlet glaciers and ice sheet drainage basins and the responsible mechanisms [8]. Advances in airborne laser ranging capabilities and Global Positioning System technology, detect ice elevation changes to within 10 cm, leading to the first comprehensive observation-based assessment of the Greenland ice sheet mass balance [9]. Ice penetrating radar improves understanding of past and current ice sheet behavior [10], and the thickness measurements enable estimates of ice flux [8,11].

Over the next five years, NASA's Ice Cloud and Land Elevation Satellite (ICESat) will measure elevation characteristics and changes of the Greenland and Antarctic ice sheets using advanced laser ranging technology. With 15 cm single-shot precision, ICESat will detect elevation changes to better than 2 cm accuracy in a 100 km x 100 km grid. It is the first mission designed specifically for ice sheet research and ICESat's 94° inclination will maximize coverage of Greenland and Antarctica. When coupled with observations from the Gravity Recovery and Climate Experiment the overall ice sheet mass balances will be more accurately assessed. An ICESat follow-on mission, planned for the 2010 timeframe, will allow for a long-term mass balance assessment

FUTURE ICE OBSERVATIONS

Beyond the ten-year time horizon new observations must measure elevation changes and mass balance parameters at spatial scales ranging from meters to hundreds of kilometers. The higher resolution observations are important because the initial responses to climatic perturbations will occur in outlet glaciers where terrain is rough, and processes are more local. These areas control discharge fluxes. Comprehensive understanding of ice sheet changes requires that they be sufficiently characterized. Initial results from the Greenland ice sheet show that dramatic changes are occurring near the margins [9]. Models linking ice sheet changes to climate variability face a major challenge in adequately capturing the temporal differences between ice sheet and glacier responses to climate change. Further understanding and predicting of contributions to sea level rise is linked to the behavior of outlet glaciers, underlying processes, and influences on the ice sheet.

In addition to detailed elevation change measurements, assessment of ice thickness and basal conditions are crucial to determine ice fluxes and controls on flow. This, too, is important at all scales. The primary challenge is in the vicinity of ice streams and outlet glaciers, where bed conditions are complex. Finally on the large scale, retrieval of internal layer structure, or isochrons, is of importance to modeling past and future ice sheet. Contained within these layers is a history of flow and accumulation that can be used to interpret present changes in the context of the past, and improve model representation of these processes.

Satellite instrument technology developments necessary for making the needed elevation change observations will require a dense array of high spatial resolution measurements, such a mapping lidar or advanced radar processing techniques, (e.g. advanced delay-doppler radar). These technologies have been demonstrated on airborne platforms and form the basis for upcoming satellite missions, ICESat and Cryosat.

Development for space-based measurements at the desired resolution and coverage requires substantial technological advances. Ice thickness measurements have been successfully completed from aircraft, however the power and antenna requirements are such that the realization of this capability is a long-term prospect. Detection of basal conditions, an important component of glacialogical measurements, is possible in theory with multi-frequency ice penetrating radar, but even a ground-based prototype does not exist. When such space-based technologies are deployed, they will revolutionize our capability of understanding glacier, ice stream, and ice sheet behavior, resolving processes of differing time scales, and accurately predicting their pending impact on sea level.

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