TROPICAL-EXTRATROPICAL INTERACTIONS, INCLUDING ENSO

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We consider interactions between the equatorial and higher latitude oceans via oceanic pathways, concentrating on the Pacific. Pathways from the tropics to midlatitudes have long been understood; the more pressing question is the extent of the midlatitude oceans' impact on the deep tropics. It is a central question for climate studies, since the tropical oceans exert a profound influence on the global atmosphere, and thus on global climate.

On short timescales, such as seasonal to interannual, there appears to be no discernable influence of higher latitudes on the tropics. The El Niño–Southern Oscillation (ENSO) cycle evolves in the tropics, influencing global climate and the global oceans, but is not affected by oceanic changes in midlatitudes. Obviously, on the longest timescales, changes in the subtropical and mid-latitude sources of equatorial waters must alter the equatorial oceans. We now have a better quantitative picture of the origins of these waters and their pathways to the tropics. Most, but not all, of this water reaches the equatorial region along the western boundary. There are some discrepancies between models and observational analyses of the magnitude of the interior flow to the deep tropics.

While we know that on short timescales the tropical oceans are self-contained, and on very long timescales the midlatitude influence is significant, intermediate timescales are less certain. In principle higher latitudes could influence decadal variations in the tropics, but studies indicate that, in fact, they do not. There are important implications for decadal variations of ENSO, and decadal modes of variability such as the PDO (Pacific Decadal Oscillation). Very recent modeling results indicate that anomalies in buoyancy forcing are the most effective extratropical means of creating tropical changes. These results await observational confirmation.

We examine recent modeling and observational results in the light of well-established equatorial ocean circulation theory, especially equatorial wave theory. Some interesting relationships emerge. Although much has been clarified sufficiently for climate studies, the extent of interior pathways to the equator and the sources of waters feeding the equatorial thermocline are still not adequately known.

WHAT DO THE LARGE-SCALE MODES OF EXTRATROPICAL VARIABILITY IMPLY ABOUT MEMORY AND PREDICTABILITY?

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In this talk, I will address three key questions regarding our understanding of extratropical climate variability: 1) What are the leading modes of variability in the extratropical atmospheric circulation? 2) What do oceanic processes imply about the memory and predictability of these modes? and 3) What do internal atmospheric dynamics imply about the memory and predictability of these modes?

Variability in the Northern Hemisphere extratropical atmospheric circulation is dominated by two principal patterns, the Northern Hemisphere annular mode (also referred to as the Arctic Oscillation and the North Atlantic Oscillation) and the wavelike Pacific-North America pattern. Variability in the Southern Hemisphere extratropical atmospheric circulation is largely dominated by the Southern Hemisphere analogue to the Northern Hemisphere annular mode, referred to here as the Southern Hemisphere annular mode. The Northern Hemisphere and Southern Hemisphere annular modes are characterized by deep, nearly barotropic structures with zonal wind perturbations of opposing sign along ~55° and ~35° latitude of their respective hemispheres. The Pacific-North America pattern is characterized by wave-like fluctuations in the geopotential height field that span much of the Northern Hemisphere, with largest amplitude over the North Pacific/North American sector. The Northern Hemisphere annular mode and the Southern Hemisphere annual mode are thought to owe their existence to the interactions between the zonal flow and transient eddies in the extratropical atmospheric circulation. The Pacific-North America pattern is thought to owe its existence to barotropic instability in the vicinity of the Pacific jet.

The aforementioned modes of variability have marked impacts on the climate of their respective hemispheres. Hence, the predictability of these patterns is clearly of practical interest. In the past decade, considerable research effort has been placed on understanding the role of the midlatitude ocean in driving low frequency variability in the Northern Hemisphere annular mode. For example, several numerical simulations have simulated low-frequency variability in the Northern Hemisphere annular mode in response to slowly evolving sea-surface temperature anomalies. However, since the results of these simulations can be interpreted as the damped thermal response of the atmosphere to prescribed SST anomalies, they do not necessarily reflect improved predictability of the climate system. In general, there is increasing consensus that the middle latitude atmosphere is only weakly sensitive to middle latitude sea-surface temperature anomalies. Considerable research effort is now focused on the role of tropical sea-surface temperatures in driving low-frequency variability in the Northern Hemisphere annular mode.

There is also increasing interest in the role of internal atmospheric dynamics in the memory and predictability of the annular modes. In particular, recent observational, numerical, and theoretical evidence suggests the dynamic coupling between the stratosphere and troposphere plays a key role in driving variability in the Northern Hemisphere annular mode on both intraseasonal and interannual timescales. The dynamics of this coupling and the attendant implications for both weather prediction and climate change are discussed. It is argued that the predictive skill that derives from the dynamic coupling between the stratosphere and troposphere is roughly comparable in amplitude to that observed in relation to the El-Niño/Southern Oscillation phenomenon, and far exceeds that observed in relation to year-to-year variability in midlatitude sea-surface temperatures.

SEA LEVEL RISE—CAN WE EXPLAIN WHAT WE MEASURE?

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On time scales ranging from years to decades, global mean sea level change results from: (1) steric (ocean water density change caused by temperature and salinity variations) and (2) eustatic (ocean mass change resulting from water exchange with continental reservoirs and ice sheets) contributions. Tide gauges data suggest that the global mean sea level has been rising by 1.5-2. mm/yr during the past century while satellite altimetry indicates a rate of rise approaching 3 mm/yr since the early 1990s. There are additional astronomical/geophysical observations (secular variations in Earth's rotation, position of the rotation pole and Earth's dynamical flattening) that can in principle offer additional constraints to the rate of present-day sea level change.

In the Third Assessment Report published in 2001, the IPCC re evaluates the steric and eustatic contributions to the 20th century sea level rise and concludes that the sum of the climate-related contributions ranges from –0.8 to 2.2 mm/yr, with a median value of 0.7 mm/yr. Although the uncertainty is quite large, this revised estimate explains only half the observed rate of rise. This is what Walter Munk calls 'The Enigma'.

In this presentation, we fist discuss observations of global mean sea level variations based on satellite altimetry and in situ tide gauges. Then we discuss climate-related processes, focusing on thermal expansion and continental water mass balance, two contributions that can now rather confidently be determined using recently available new global data sets. We show that Topex/Poseidon-derived sea level rise is almost totally explained by thermal expansion. For the last four decades, warming of the oceans contributes to an average rate of sea level rise of 0.5 mm/yr. But the data also suggest an acceleration of the thermosteric sea level rise around the early 1990s. We next discuss possible causes of the discrepancy between tide gauge observations and climate-related contributions. We show in particular that historical tide gauges used to determine the 20th century sea level rise are unable to capture the regional variability of the thermosteric trends, withn as plausible consequence, an overestimate of the observed sea level rise. We present a first determination of the land water mass contribution resulting from change of the global water cycle. This component amounts to 0.2 mm/yr for the past 2 decades, a small but not totally negligible contribution. Finally, we discuss astronomical observables and show that these do not represent strong constraints to values of present-day sea level rise. To conclude, perspectives expected from the recently launched

JASON and GRACE missions for precisely measuring global sea level change (with JASON), and determining land water mass contribution (with GRACE) and thermal expansion (by combining JASON and GRACE data) are briefly discussed.

THE OCEAN COMPONENT OF CLIMATE MODELS – WHAT RESOLUTION AND PARAMETERISATIONS ARE REQUIRED?

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The first goal of WOCE was 'to develop ocean models suitable for predicting climate change and to collect the data necessary to test them'. Has this been achieved and if not, what remains to be done? At the start of WOCE in the mid-1980s, only very few centres had the resources to attempt global ocean or climate simulations, and these were severely limited by the computing power available at the time. However, as the founders of WOCE correctly foresaw, the WOCE period saw a huge increase in the computer power available and in the sophistication of the models used. This has led to developments in the realism of models, largely in the form of better resolution and more sophisticated representation of the physics of the ocean. Coupled climate models are now a valuable tool to a wide range of researchers interested in understanding historical climate change and in predicting future climate.

The long integration times required for climate work still restrict the resolution that can be used, and it is only very recently that early efforts have been made to run climate models at 'eddy-permitting' resolution. These preliminary results have shown that simply increasing resolution does not guarantee a more accurate representation of all important climate variables, and that great care is required in the configuration of the models and in the atmosphere-ocean coupling. These early efforts will provide some insight into the question of whether the mesoscale needs to be resolved, but the question will remain an open one at least until new computers allow genuinely 'eddy-resolving' climate integrations to be performed over the next few years.

Advances in subgrid parameterisations, particularly of isopycnal mixing due to mesoscale processes, have led to great improvements in the basic climate simulations achievable at relatively coarse resolution. Ultimately, predictions made using such models will have to be tested against higher resolution models described above. The scales of processes believed to be responsible for diapycnal mixing are such that these processes are unlikely to be resolved in models in the near future. Observational understanding obtained during WOCE has emphasised the strong horizontal inhomogeneity of diapycnal mixing, but only very few numerical experiments have been made as yet to explore the importance of this inhomogeneity for the large scale circulation. Development of parameterisations in this area is still limited by lack of observations, despite the great progress made during WOCE.

Looking to the future, the following are therefore likely to be important areas of development in ocean climate models over the next few years: improved parameterisation of diapycnic mixing processes, understanding the importance of mesoscale processes in climate through high resolution models, more flexible coordinate systems (e.g. adaptive meshes), and inclusion of biogeochemical processes. Current developments in supercomputing technology are now making a serious attack on the questions of the title possible, and some real progress can be expected by the time of the IPCC Fourth Assessment Report in 2007.

HOW HAVE WOCE OBSERVATIONS CHALLENGED OCEAN MODELS?

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WOCE produced high-quality observations on unprecedented temporal and spatial scales during the 1990s. Over the lifetime of WOCE, improvements in supercomputing technology provided the resources whereby basin and global ocean models could be run at eddy-resolving (5-10 km and 40-50 levels) rather than eddy-permitting (25-40 km and 20-30 levels) resolutions. Prescribed atmospheric forcing is no longer limited to climatological fluxes or restoring to surface climatologies.

Realistic fluxes, computed using bulk formulas that combine model sea surface temperature and atmospheric quantities, can be used to force hindcast simulations of the past several decades. Improved topography data sets have become available and improvements to numerics and to parameterizations of unresolved ocean processes continue. These advances have provided the means of simulating the mean and varying components of the circulation. In addition, ocean models coupled to air/ice/land components can now be run at close to eddy-permitting resolutions for centennial time scale climate applications. The WOCE data have been an integral part of these developments by providing a yardstick to assess the realism of the ocean simulations as well as a means to guide improvements to model parameterizations.

Quantitative measures of surface energy levels, intrinsic scales, current strengths and locations, and modes of variability have been obtained on basin and near-global scales from TOPEX/POSEIDON and ERS1 and 2 altimeters and surface drifting buoys. They have been used to gauge improvements in the realism of the modeled ocean states as a result of using higher model resolution and/or more realistic surface forcing. The temporal evolution of sea level height anomaly from altimeters and tide gauges has been compared with that from models. Hydrographic and XBT data have been used to understand the impact of surface buoyancy forcing on water mass formation and meridional heat transports. Comparisons of property distributions from WOCE-based climatologies and ocean models provide a guide to the accuracy of water mass pathways and thermocline structures in the model. Current meters deployed in boundary currents and across choke points have measured the mean and variability of transports, key indicators of model skill. Vertical structures of upper-ocean jets as depicted by models have been compared with ADCP data. Longer-term data sets such as high-resolution repeat XBT lines provide the opportunity to evaluate intraseasonal through interannual variability in the models. Finally, refinement is needed of methods to simulate PALACE floats, tracer releases, and deep Lagrangian floats, instruments that have revealed new and exciting aspects of the circulation beyond the reach of pre-WOCE methods.

The WOCE data have either motivated, or been used to guide, improvements to parameterizations of mixed layer, mesoscale eddy, and bottom boundary effects. Continued improvements of such parameterizations, hybrid co-ordinate ocean models that merge the strengths of existing ocean models, forcing fields constructed from satellite products, and synergistic data assimilation studies will continue to improve the representation of ocean processes in models to be used for ocean and climate studies.

THE ATLANTIC OCEAN: FROM THE METEOR EXPEDITION THROUGH WOCE

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The Atlantic Ocean is the smallest of the world's oceans. When WOCE was being planned during the 1980s, the Atlantic was the best sampled of the global ocean. The Meteor Expedition of the 1920s, the IGY of the 1950s, the hydrography of the 1960s and the Long Lines and other programs of the 1980s had mapped the large scale water mass structures and provided good evidence of its variability. From the 1970s onward, developing deep sea moorings, subsurface Lagrangian floats and surface drifters had also provided preliminary estimates of the transports of the major currents as well as the distribution of kinetic eddy energy in the North Atlantic.

The WOCE Atlantic program focussed on meridional circulation of the bottom, deep and intermediate water masses in both the North and South Atlantic and documented significant changes from the earlier surveys. Direct measurements were made of the transports of both the wind driven and deep western boundary currents along the full length of the Atlantic basin. These coupled with the Lagrangian measurements made by the surface drifters and by sub-surface floats (ALACE, PALACE, SOFAR and RAFOS) and the sea surface topography from satellite altimetry has provided a new description of the circulation of the entire basin. The final intensive survey of the North Atlantic with its particular focus on the sub-polar gyre has changed our view of this region's circulation.

During WOCE, a number of process experiments were carried out within the Atlantic. The subduction experiment and the North Atlantic tracer release experiment provided direct estimates of mixing and circulation in the upper waters of the sub-tropical gyre. The deep basin experiment in the Brazil Basin showed the important roles that topography plays in ocean mixing. The repeat hydrography in the North Atlantic has documented the remarkable continued freshening of all of the deep and intermediate water masses of North Atlantic. Because of the WOCE data policy, analysis of these changes along the pathways has been possible. These analysis have pointed to the important role that downstream mixing and entrainment play in determining these deep water properties.

Finally, the Atlantic has continued to be a focus for the computation and evaluation of air-sea flux climatologies. The differences between the various climatologies and reanalysis products are still disappointingly large. As CLIVAR focuses on climate variability of the coupled ocean-atmosphere system, the uncertainty in knowing the true air-sea fluxes remains a significant limitation.