WHY DID WE DO WOCE?

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WOCE was conceived in the late 1970s—a generation ago. It is not so easy to recapture the thinking of the time, nor to readily distinguish the field as a whole from what WOCE accomplished. At the Halifax Conference, R. Stewart laid out some of the international scientific and political considerations. I will try to recapture some of the primarily scientific challenges, circa 1979, in a more personal view, of the motivations for the Experiment. These include the intense focus at the time on processes (internal waves and mesoscale variability particularly), the absence of any global scale observations, the technical possibilities of certain space borne measurements (altimetry, scatterometry, gravity), an emerging generation of in situ technologies, the need to address the growing calls for understanding of the CO_2 transient, the seemingly inexorable growth in numerical model skill, and other elements such as the perceived ongoing intellectual fragmentation of the field. Some of what happened now appears, to a later generation, to have been inevitable. Whether that is actually true is worth exploring. Many of the problems now facing the field are different, but analogous to, those we faced in 1979. Whether an adequate response can be regarded as also inevitable, is a question of great scientific urgency.

SATELLITE MICROWAVE OBSERVATIONS OF THE GLOBAL OCEAN

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The satellite observations most relevant to WOCE are altimeter measurements of sea surface height (SSH) and scatterometer measurements of surface winds. At the outset of WOCE planning in 1980, the only high-quality satellite altimeter and scatterometer data available were from the proof-of-concept Seasat mission. Although Seasat lasted only three months from July to October 1978, it succeeded in demonstrating that altimeters and scatterometers could meet the science requirements for measurements of SSH and surface winds, thus providing the only viable means for globally observing surface geostrophic currents and wind forcing.

The WOCE field program formally began in 1991. The ERS-1 satellite launched in 1991 and was succeeded by ERS-2 in 1995. Both satellites carried an altimeter and a scatterometer. The TOPEX/POSEIDON (T/P) altimeter launched in 1992 and continues to operate now, long after the end of the WOCE field program. To the uninitiated, it would appear that there was a careful coordination of the timing of WOCE and the satellite programs. In actuality, the coincidence in the timing was mostly a matter of luck, as will be summarized in this presentation.

Fortunately, the highly accurate T/P altimeter measured the time-variable ocean circulation throughout nearly all of the WOCE observational period, thus providing a context of the large-scale, low-frequency variability in which to interpret much of the WOCE in situ data. If the highly accurate T/P data had not been available, the ERS-1 and ERS-2 altimeters would have received more attention than they have to date. T/P data reveal numerous details of the spatial and temporal variability of large-scale and mesoscale ocean circulation that were not previously known. T/P has also provided a valuable global dataset for evaluating the quality of ocean general circulation models.

Scatterometry has had less impact on WOCE for a variety of unfortunate reasons. The narrow-swath scatterometers on the ERS satellites limit the space-time resolution of wind fields that can be constructed from the data. The dual-swath NSCAT scatterometer doubled the sampling density but the mission ended prematurely after only nine months. The wide-swath QuikSCAT scatterometer with more than three times the sampling density of the ERS scatterometers has now provided more than three years of data. Although the July 1999 start of the QuikSCAT data record was too late to benefit the interpretation of the WOCE observational data, the QuikSCAT data reveal previously unknown features in the surface wind stress field that have important implications for ongoing and future studies of air-sea interaction and wind-forced ocean circulation.

The outlook for continued satellite data is very promising for perhaps a decade. After that, however, the future of precision satellite measurements of SSH and surface winds is much less certain.

THE INFERRED THREE-DIMENSIONAL VELOCITY FIELD

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A variety of data sets are available at the end of WOCE to address the problem of determining the 3-D velocity field of the ocean. These include tracers, hydrography, satellite altimetry, current meter moorings and drifters of various descriptions. Ultimately, we can hope that all of this information will be combined with a dynamically correct numerical model to establish the time dependent velocity field during the WOCE period and to allow prediction into the future. In several other talks during this conference speakers will address the state of the ocean from one or more of these data perspectives. This talk will concentrate on what has been learned from the perspective of direct measurement of horizontal velocity using surface and subsurface drifters, arguably the most novel contribution of WOCE to the description of the general circulation.

A considerable achievement of WOCE has been to employ a host of quasi-Lagrangian drifters over the World's oceans. Surface drifters have been deployed pretty much globally in sufficient numbers to get a reliable maps of means and variances except at high latitudes. ALACE, RAFOS, MARVORs and the like have been deployed in unprecedented quantities in each ocean basin and are revealing unexpected complexities of the subthermocline circulation. This talk will concentrate on the similarities in circulation features revealed by these techniques. It is clear that topographic influence of features such as the midocean ridges, trenches and seamount chains can extend up to the surface. It is also clear that some portions of the circulation are quite barotropic whereas others are not, with wind-driven gyres predominating in the upper ocean and zonal bandedness characteristic of the deep ocean.

The drifters also reveal, although more crudely, the time dependent ocean. Surface drifters show distributions of velocity variance which highlight the meandering boundary currents, the ACC and the tropical regions in a similar way to that seen by the TOPEX/Poseidon altimeter. In the lower latitudes of the deep Pacific and Atlantic there is a quasi-annual signal, perhaps related to the baroclinic Rossby waves that have been seen at the sea surface in altimeter data.

A prime justification for the widespread deployment of deep drifters was their potential use in constraining inverse models. Although this application is only beginning some attempts in this direction will be presented. Comparison of the circulation features discussed above with relevant numerical models, where available, will be made.

The talk will end with a discussion of where and how drifters might, in the future, contribute to the understanding of ocean circulation and its role in climate change.

NEW TECHNOLOGIES: DEVELOPMENTS DURING WOCE AND WHAT THE FUTURE MIGHT HOLD

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WOCE has brought about major technological advances in a variety of ocean observing fields. The developments can broadly be classified into techniques that: (a) were already used widely before WOCE but experienced significant increases in accuracy or efficiency; (b) already existed before WOCE but were still in their infancy then and which really developed and showed their full potential subsequently; or (c) were more or less invented or created during WOCE.

Category A includes back-bone WOCE methods like ship-based hydrography using CTDs and transient tracers, and current meter moorings. These are widely known and will not be analyzed further here. The second category refers to techniques like satellite altimetry, shipboard ADCP, surface flux observations, surface drifters, acoustically tracked floats, and acoustic tomography. Of these, satellite altimetry will be used as an example of a method having provided a real breakthrough during WOCE. Category C includes newly developed approaches like profiling floats and deliberate tracer release experiments. These techniques, and the benefits they have brought during WOCE, will be discussed in some detail.

Apart from the advances that were made, some attention will also be given to cases where technology fell behind expectations or where developments have not yet been used to their full potential.

The final part of the talk will look at future technologies which will greatly enhance our capabilities to observe the ocean. In the near-term, this includes techniques that either exist as prototypes already or are on the drawing board. The longer-term perspective is more uncertain, but should result in a comprehensive observing system covering many space and time scales, all three dimensions of the ocean, and a large variety of variables and processes.

NEW INSIGHTS FROM MODELS

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Analytical and numerical models have helped us understand the ocean circulation. Until recently, this comprehension has been qualitative, restricted to simple balances including only a few processes, or restricted to a small portion of the spatio-temporal spectrum of ocean motions. Now, high resolution global or basin scale models have become realistic enough to allow quantitative tests of our ideas about the ocean circulation and its variability.

We present instances of new insights provided by those models, mainly taken from the Atlantic and Southern oceans. Models have emphasized new currents (like the East Queensland current or the Zapiola gyre) and a new route for the global conveyor belt (the Tasman leakage). They have changed our views of some dynamical mechanisms driving those currents. One example is the Azores current in the Eastern Atlantic. It was previously pictured as a branch of the Gulf Stream system but may also be considered as a response to entrainment in the Gulf of Cadiz. Other examples are found in the Southern Ocean region.

A skillful ocean model for climate must represent accurately the processes by which the ocean transports heat and freshwater. Models have contributed to update our views of those mechanisms, for example by emphasizing the role of the wind in the seasonal and interannual variability of heat transport, or quantifying the direct and indirect roles of mesoscale eddies.

We conclude by discussing the increasing role of models in climate studies, from nowcasting to forecasting.

THE PACIFIC OCEAN

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Pacific general circulation and climate studies resulting from basin-scale observations and modeling of the 1990s are reviewed. WOCE and related observations pulled oceanography well beyond testing the basic mechanisms of the mean wind-driven circulation and planetary wave propagation, which were important research outcomes of the 1980s. The plethora of WOCE observations and model results are reviewed in terms of the mean upper ocean circulation and ventilation, impacts of extra-tropical and thermocline waters on tropical climate, circulation variability as assessed from in situ and satellite measurements and from models, assessment of decadal climate patterns such as the PDO, new information about circulation at mid- and abyssal depths, and the role of the Pacific in global transports and overturning.