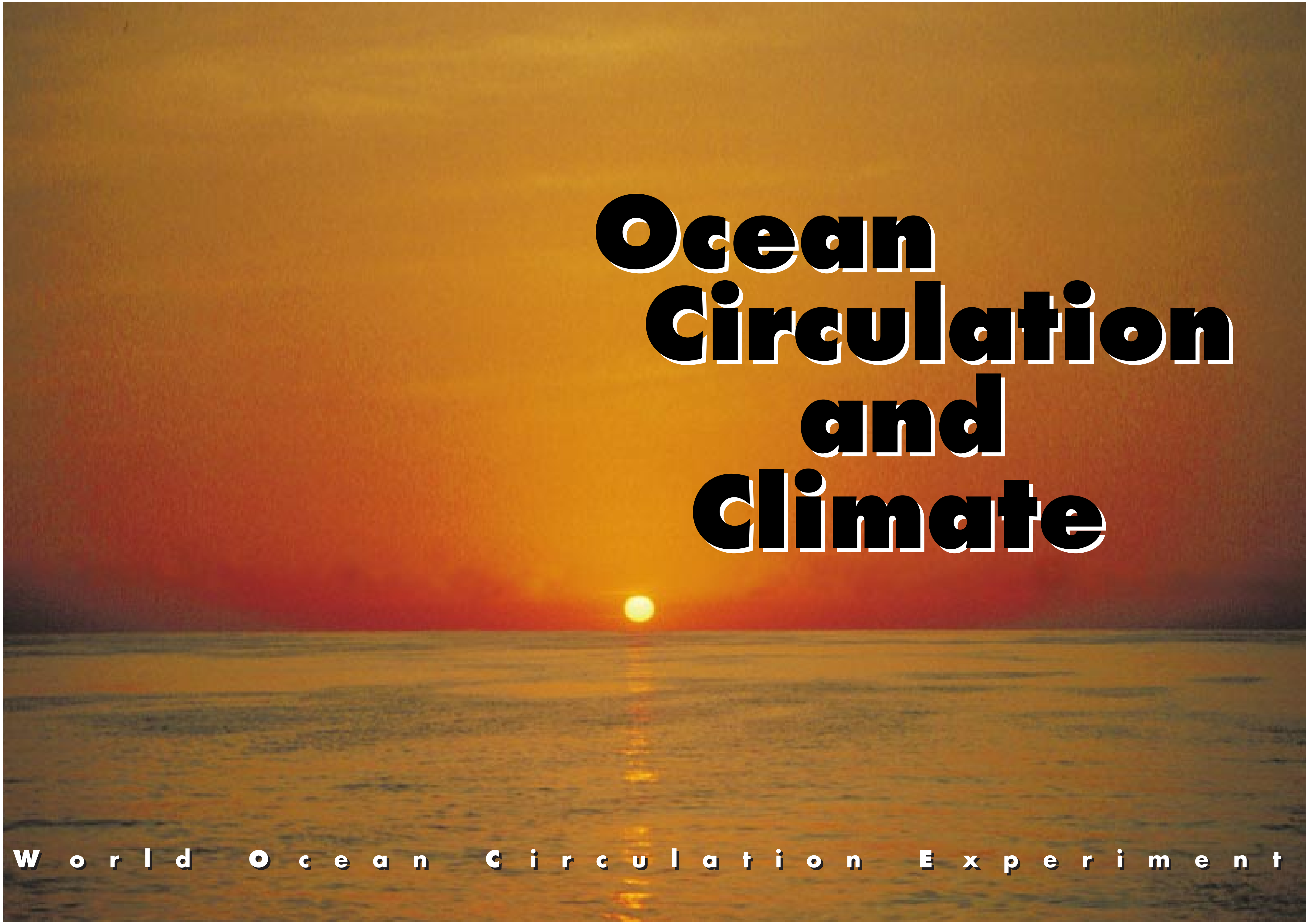

Ocean Circulation and Climate

World Ocean Circulation Experiment

Contents

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Introduction

The oceans, by virtue of their large capacity to store and transport heat, are an essential part of the physical climate system. They are also an important component in the global carbon cycle. Containing 96% of the earth's water they dominate the hydrosphere and play a key role in natural climate variability at seasonal, interannual and longer timescales, as well as in anthropogenic climate change.

It is vital therefore that a study of the ocean and its circulation should be an integral part of the World Climate Research Programme (WCRP). The World Ocean Circulation Experiment (WOCE) was designed to improve the ocean models necessary for predicting decadal climate variability and change.

This brochure summarises why and how WOCE came about, and its objectives. It also illustrates some of the progress to date and what outstanding problems remain to be solved.

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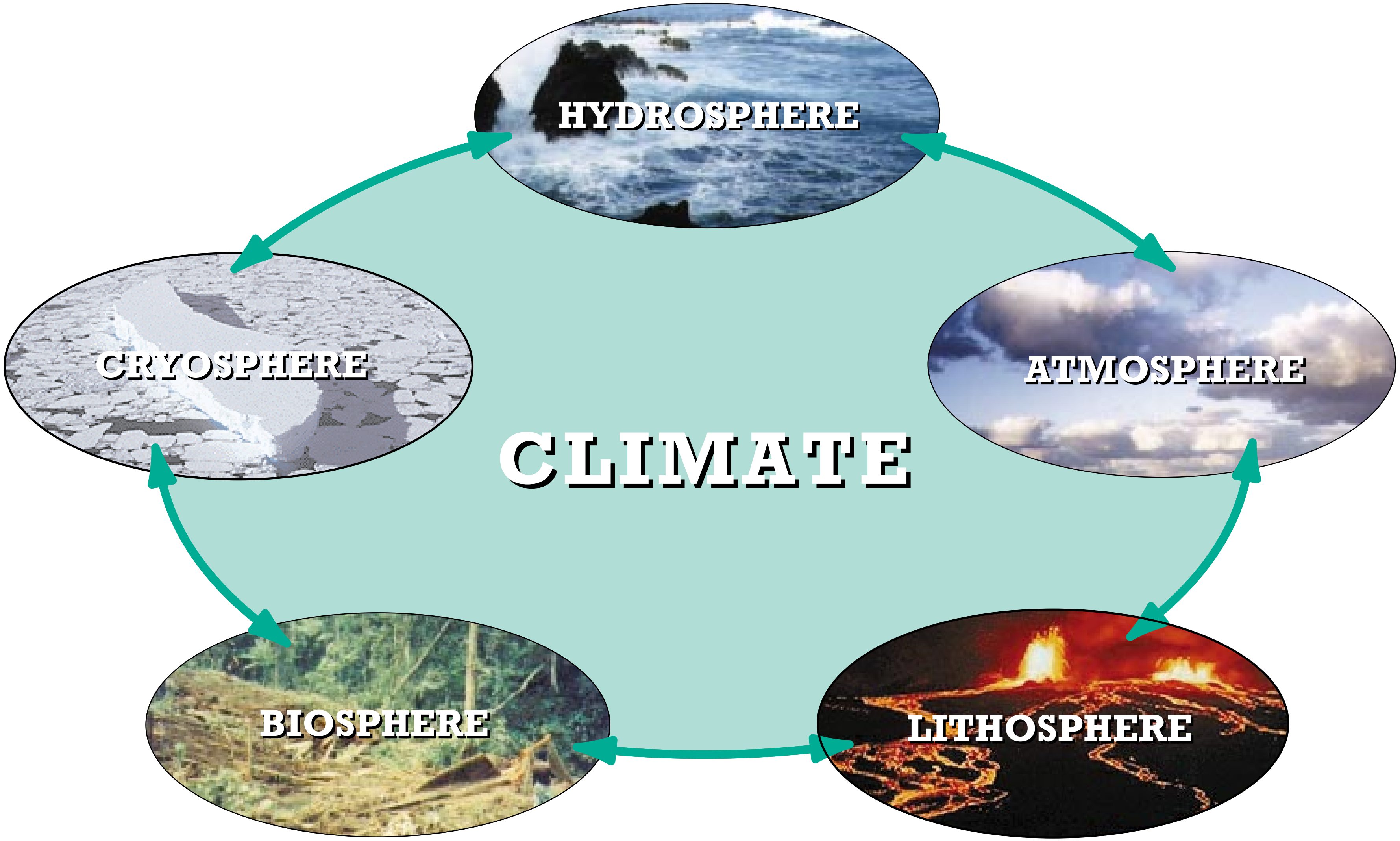
Elements of the Climate System



Why and How WOCE Came About

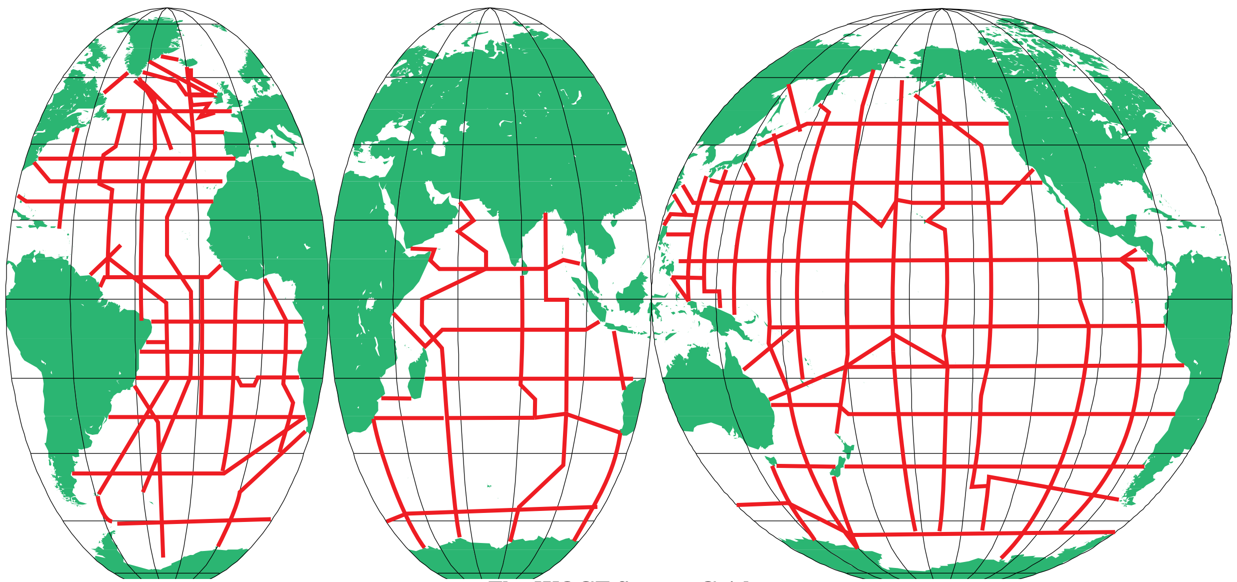
'Develop the ability to describe and model ocean circulation'

The WCRP carries out the research required to allow climate prediction on a range of timescales (months, years and decades). When WCRP was conceived, a fundamental limitation to predictions on long timescales was an inability to describe and model the oceans and their circulation. This stemmed in part from our limited ability to observe the oceans globally and from inadequate computer power.

In 1978 the short–lived US Seasat satellite showed that ocean currents, temperatures and winds could be monitored globally. This, and rapidly deveoping super-computer power, meant that by the early 1980's a World Ocean Circulation Experiment to address the role of ocean circulation in the climate system could be planned.

Scientists in 30 countries developed and committed their national resources to an inter-nationally–agreed observational experiment to be carried out between 1990 and 1997. The plan required a significant expansion of sea–going capabilities. The timing was designed to coincide with the launch of a new generation of ocean–observing satellites.

WOCE observations are almost complete but research will con-tinue in a phase of Analysis, Interpretation, Modelling and Synthesis (WOCE AIMS) until 2002. WOCE will provide the understanding of the ocean required for climate prediction as well as providing benefits to a wide range of research and operational marine activities not necessarily related to climate research.



The WOCE Survey Grid

The WOCE Objectives

WOCE has two major goals

Goal 1

To develop ocean models useful for predicting climate change and to collect the data needed to test them.

- How much heat and fresh water do the oceans transport and exchange with the atmosphere and cryosphere?
- How are the ocean currents driven and the temperature and salinity determined by the atmospheric forcing?
- How variable is the ocean? What role is played by the small eddies that fill the ocean?
- How do the properties that are determined by the ocean's interaction with the atmosphere move around the ocean?

Goal 2

To determine the representativeness of the WOCE data sets for the long-term behaviour of the ocean and to find methods for determining the long–term changes in ocean circulation.

- How do WOCE observations compare with earlier measurements? Can we quantify changes over tens of years?
- Can we identify cost–effective ways to monitor future change? What parameters should we measure and how often?

Intergovernmental Panel on Climate Change 1995
Excerpts from the
Summary for Policy Makers

"The increasing realism of simulations of current and past climate by coupled ocean-atmosphere models has increased our confidence in their use for projection of future climate change".

"Many factors currently limit our ability to project and detect future climate change. To reduce uncertainties further work is needed on the following priority topics:

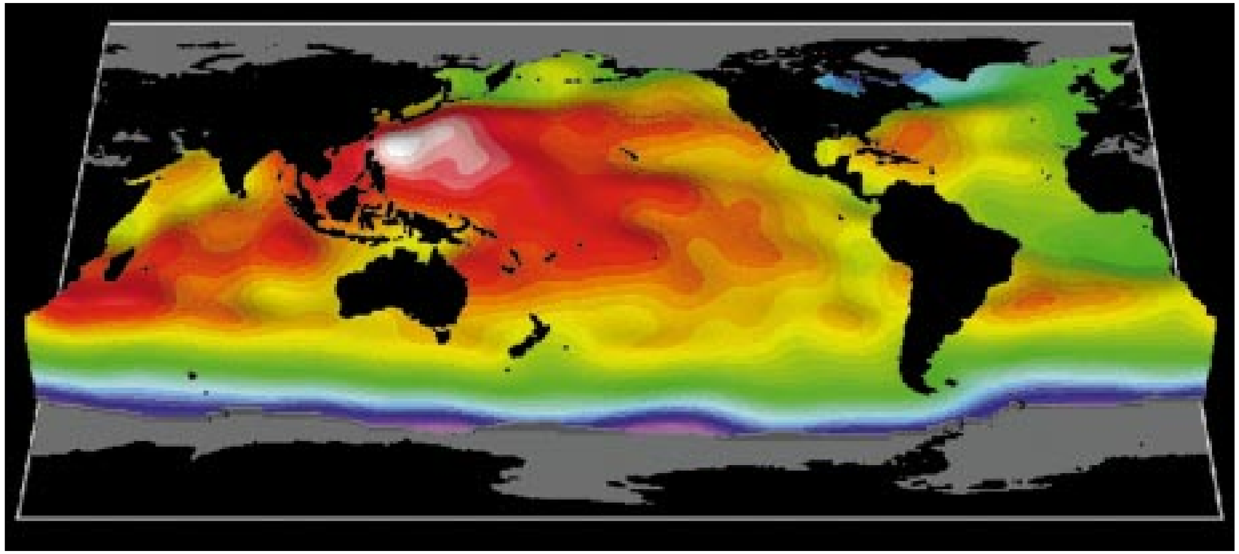
- Representation of climate processes in models, especially feedbacks associated with clouds, OCEANS, sea ice and vegetation…
- Systematic collection of long–term instrumental and proxy observations of climate system variables (eg …ocean characteristics…) for the purposes of model testing".

Collecting Ocean Data for WOCE

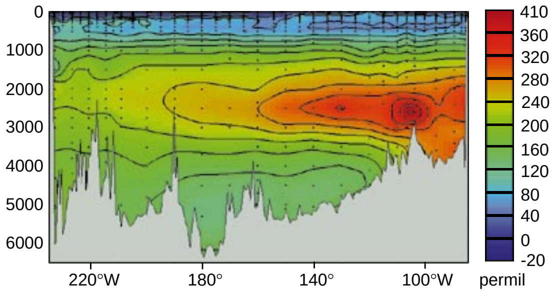
'New earth observing satellites and…'

Central to WOCE has been a global survey of the oceans' temperature and salinity distribution and a number of chemical tracers (nutrients, dissolved oxygen, CFC's, Tritium/Helium, C^{14}). These observations allow the properties, pathways and rates of watermass movements to be determined. Research ships had to be modernised to cope with the large science teams and new equipment required for this survey.

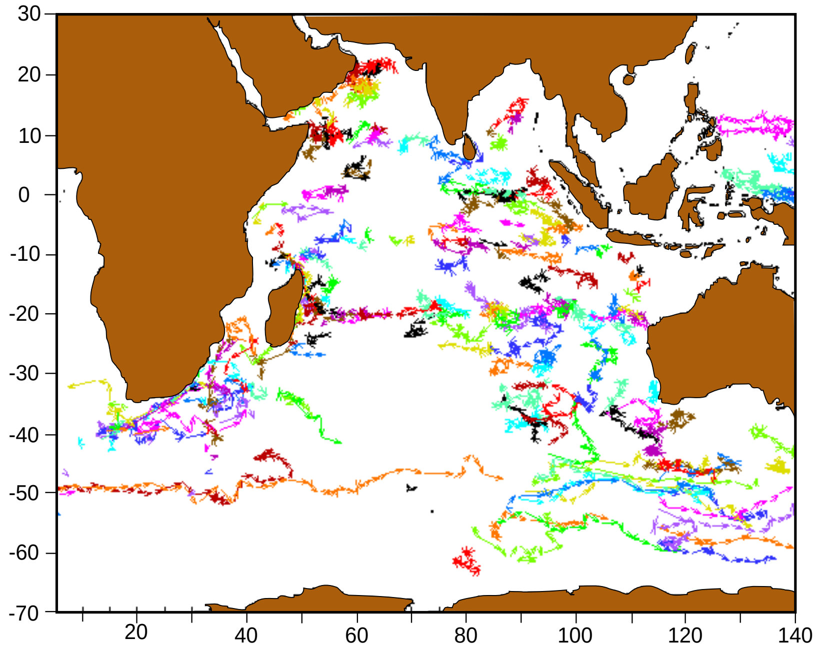
The European satellites ERS–1 and ERS–2, and the US/French satellite TOPEX/POSEIDON used by WOCE have revolutionised our view of the oceans, their circulation and the atmospheric forcing. Global satellite measurements of sea level (accurate to 3 cm), and its slope, allow the variations of surface currents to be repeatedly determined.



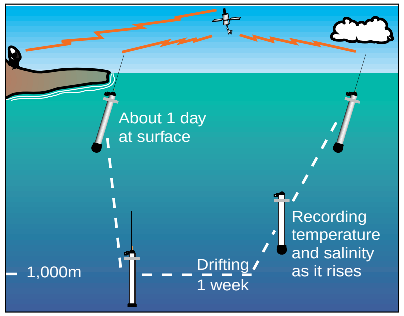
Sea Surface height from the TOPEX/POSEIDON satellite.
Currents are strongest where slopes are greatest. (JPL, USA)



Deep Pacific Helium Plume at 10°N.
(W. Jenkins, USA)



ALACE float tracks from the Indian Ocean. (R. Davis, USA)

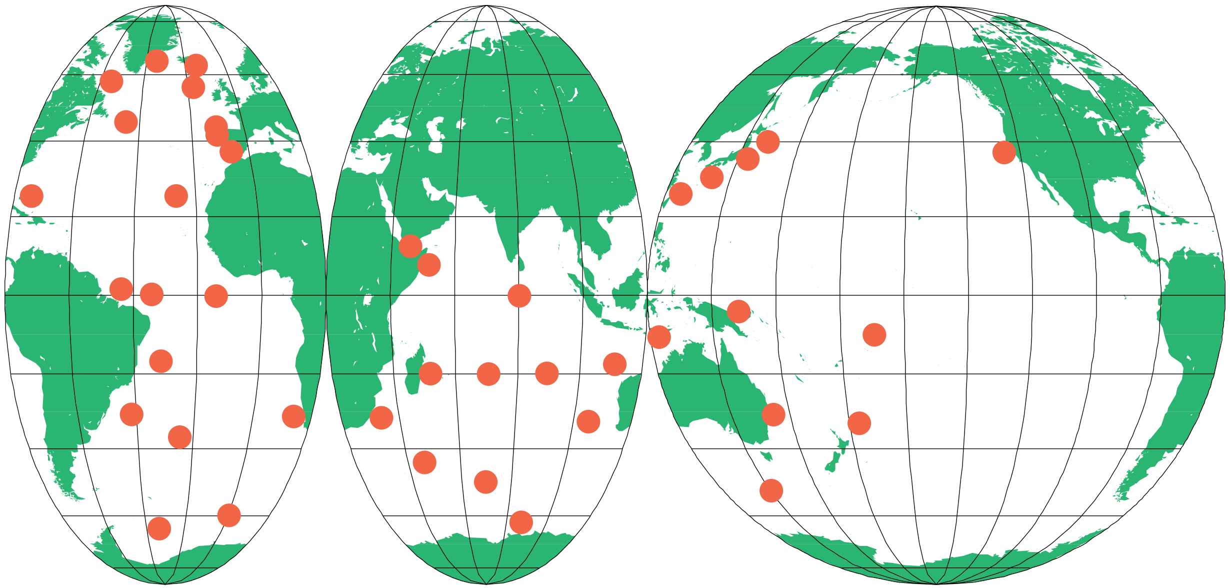


Schematic of ALACE operation. (WHOI, USA)

Mooring equipment ready for deployment. (SOC, UK)

The strength of the WOCE dataset lies in its global distribution and the success of efforts to ensure all observations are made to the highest possible standards. Measurement "to WOCE standard" has become a benchmark in ocean observations.

Moored and drifting buoys, sea level measurements and estimates of the transfer of heat, water and momentum between atmosphere and ocean have all contributed to a new and comprehensive global data set. The Autonomous Lagrangian Circulation Explorer (ALACE) float was one of the developments especially designed for WOCE to make global observations. The float drifts with the currents at 1 km depth and surfaces every week to report its position and data to a satellite.



Location of WOCE Current Meter Arrays

'…an expansion of sea-going capabilities'

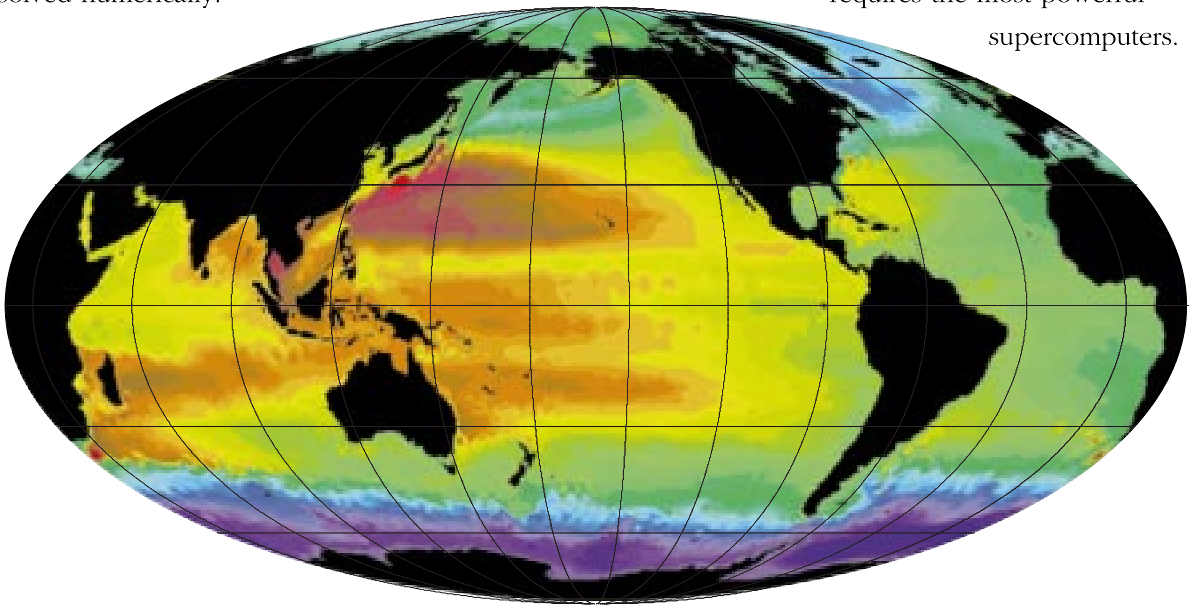
The Development of Ocean Models

'Resolving the small scales requires powerful computers'

Estimating decadal variations in climate, either natural or anthropogenic, requires models of the global ocean. These models represent physical processes occurring within the ocean and exchanges between the atmosphere and the ocean by equations that are solved numerically.

Many processes occur on small (tens of kilometres) scales. The most important ones must be represented in the models, either explicitly or by reliable parameterisations. Those that were least well understood were measured in WOCE.

The most advanced global ocean models now have resolutions of order one–sixth of a degree (17km) and up to 40 levels through the full 6 km ocean depth. Ocean models must be run for hundreds of "model years" to reach a steady state and then tested by comparison with observations such as those from WOCE. This requires the most powerful supercomputers.



A global model of the sea surface height pattern due to surface currents.
Note that the small eddy–scales can be seen. (OCCAM, UK)

Reliable estimates of future ocean conditions require knowledge of the present state of the ocean. This is best achieved by assimilating satellite and in–situ observations into models. While data assimilation is now common in weather forecasting, it is in its infancy in oceanography. Data assimilation, one of the main tasks of WOCE AIMS, will require training of a new generation of oceanographers and access to the most powerful supercomputers.

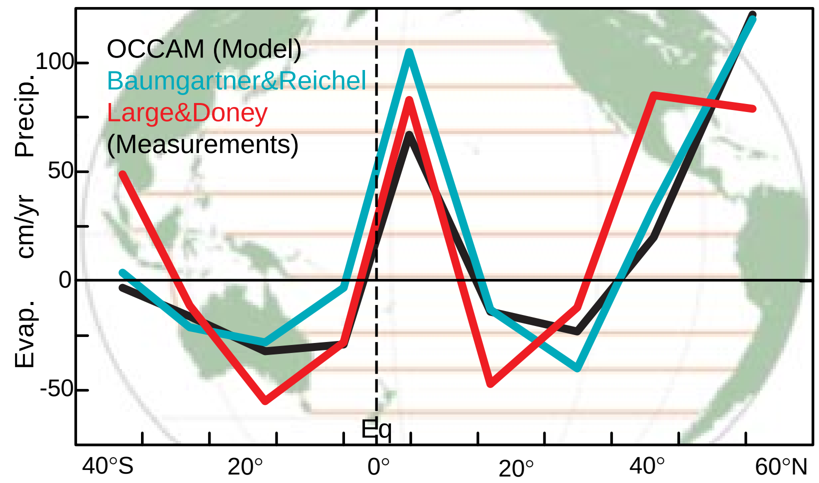
Heat and Fresh Water Transport

How much heat and fresh water do the oceans transport and exchange with the atmosphere and cryosphere?

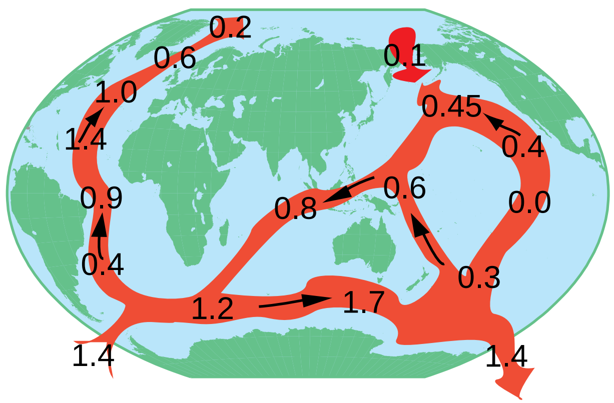
The ocean circulation is global. It is driven by winds, and by exchanges of heat and freshwater with the atmosphere (through precipitation and evaporation), and with the cryosphere (by ice formation and melting).

Ocean currents transport warm water polewards mostly near the surface along the western side of ocean basins and return cooler, denser water equatorward in the interior. These ocean currents act to redistribute heat and fresh water around the globe.

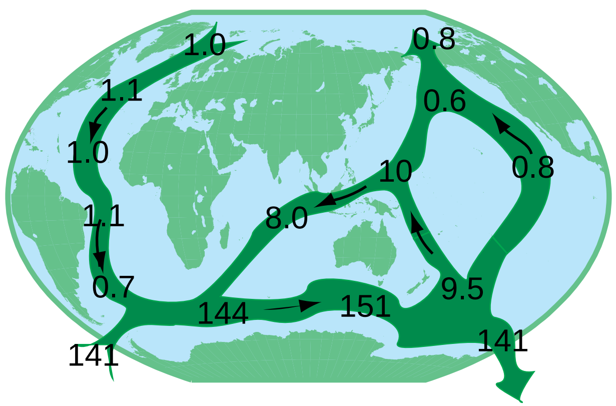
A key test of climate models is their ability to reproduce the measured transports of heat and fresh water in both the ocean and the atmosphere. Global estimates of ocean transports have already been made from pre–WOCE data. From the more extensive and superior WOCE data, improved calculations will undoubtedly result, and a key test of the new determinations will be compatibility of implied and independently measured exchanges across the sea surface.



Estimates of evaporation and precipitation for the Pacific from a model and from two climatologies. (P. Saunders, UK)



Ocean transport of heat in Petawatts (10^{15} watts). 1 PW is about 60 times the global consumption of energy. (A. McDonald and C. Wunsch, USA)



Fresh water transport in millions of cubic metres (approx. tonnes) per second, (A. McDonald and C. Wunsch, USA)

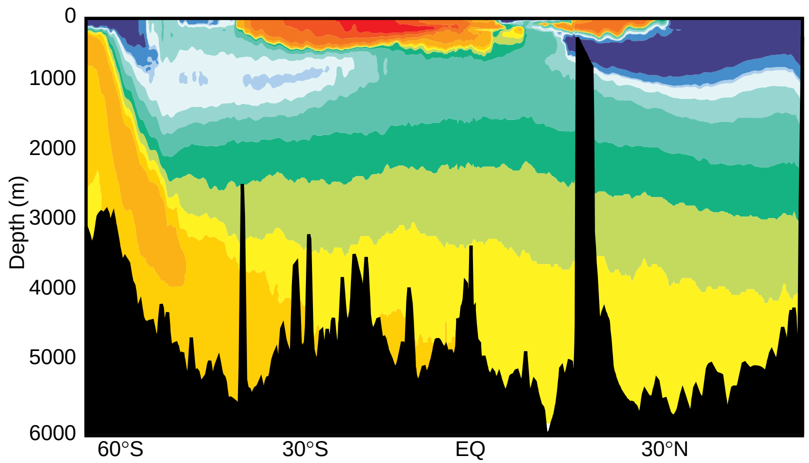
Ocean Currents

How are the ocean currents driven and the temperature and salinity determined by the atmospheric forcing?

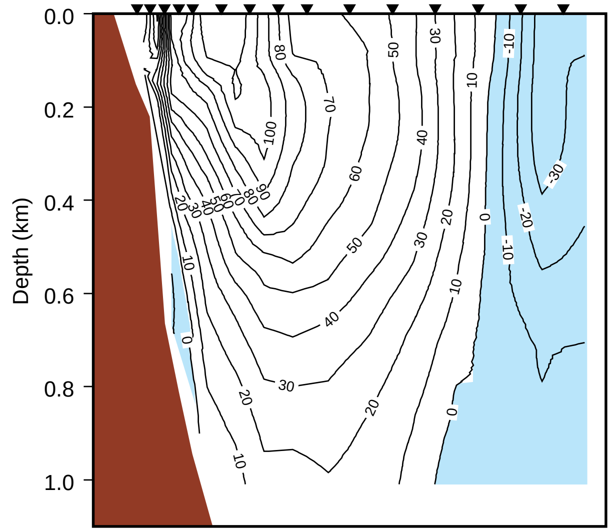
Large–scale ocean currents are driven by the winds and by changing ocean density at the surface. Before WOCE, only a few of the largest currents had been measured. During WOCE, the transports of all the major currents, Gulf Stream, Kuroshio, Antarctic Circumpolar, Agulhas, Brazil, East Australian and Malvinas currents were measured.

Their variability was also determined for the first time. This, together with the observed variability of atmospheric forcing, will allow theories of ocean dynamics to be tested.

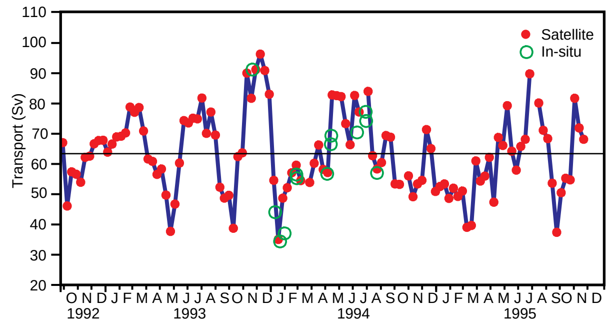
One of the key processes in determining the temperature and salinity in the ocean interior is the entrainment of winter–cooled water. WOCE studied this process at both middle and high lattudes.



12000 km Pacific salinity section from the Antarctic (left) to Alaska (right). It shows water modified in the Antarctic descending to the ocean floor and into the interior. (L. Talley, USA)

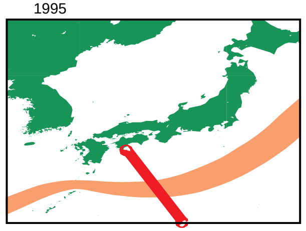


A section through the Kuroshio current showing the magnitude (cm/s) of the eastward flow.



Kuroshio transport calculated by combining satellite and in–situ data (units are millions of cubic metres per seond). (S. Imawaki, Japan)

A variety of model formulations is being used to determine which best represents the observed processes.



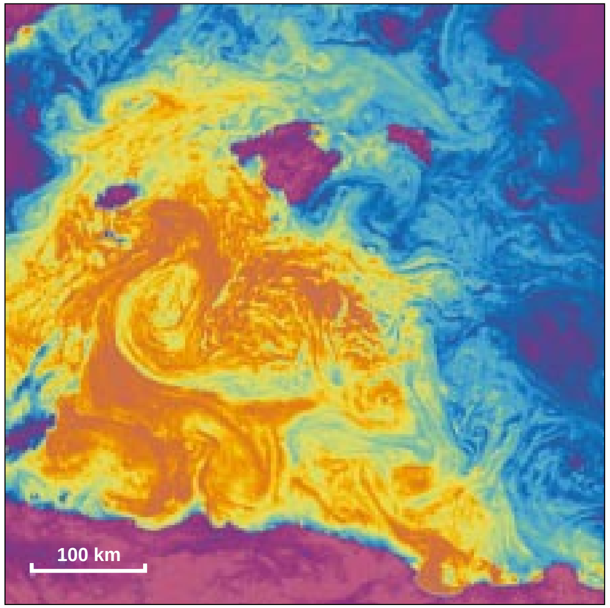
Ocean Variability

How variable is the ocean? What role is played by the small eddies that fill the ocean?

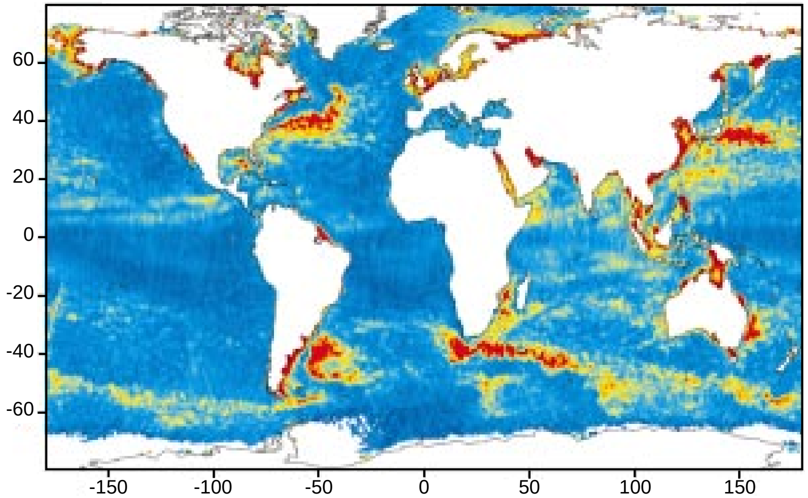
The atmosphere is full of cyclones and anticyclones that give us day–to–day changes in weather. The ocean is full of the same type of features, eddies and wave–like motions. However the ocean features are much smaller (typically 100 km diameter), longer–lasting (identifiable for months to years) and slower moving, taking around 100 days to pass any point.

To determine the average properties of the ocean, we have to assess how much the eddies will “contaminate” our measurements. The eddies also do much of the mixing in the ocean and transport properties even if there is no average flow.

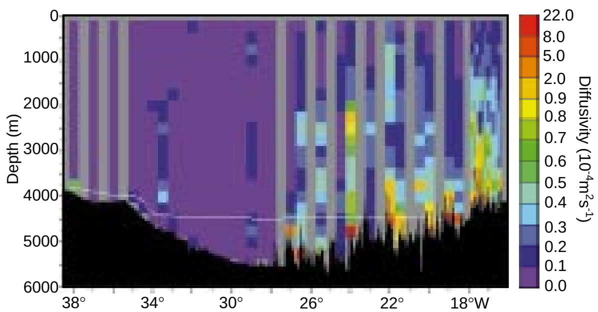
WOCE measurements have shown how effective vertical mixing is in the ocean interior and have already changed our ideas of where such mixing occurs.



Satellite infrared image of surface temperatures showing the small scales that models need to represent. (ERS–1, ESA)



Satellite altimeter data showing areas of strongest eddy variability close to major current systems. (M. Jones, UK)



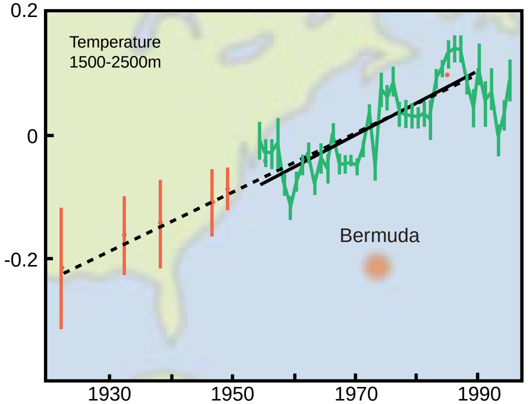
A 2000 km section in the South Atlantic running eastwards from the Brazil coast. It shows energetic mixing penetrating up through most of the ocean depth, over rugged topography in mid–ocean. (J. Toole, USA)

Ocean / Atmosphere Interaction

How do the properties that are determined by the ocean's interaction with the atmosphere move around the ocean?

Observations from satellites and merchant ships reveal sea surface temperature and salinity anomalies that persist for years. Such anomalies result from changes in rainfall and evaporation, from heat exchange with the atmosphere and from ocean circulation changes.

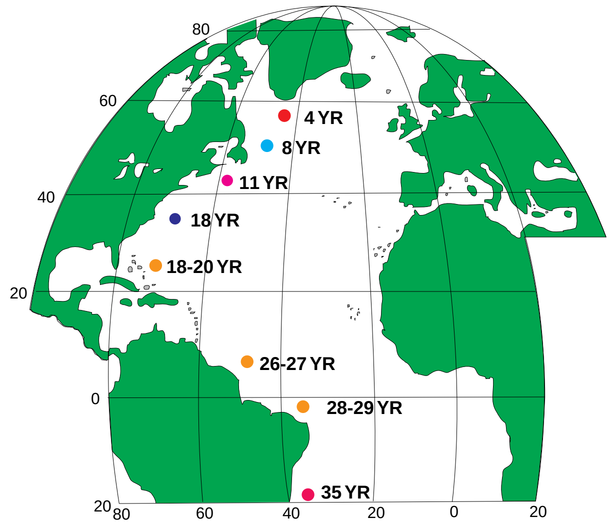
There are few measurements below the ocean surface over periods of ten years or longer.



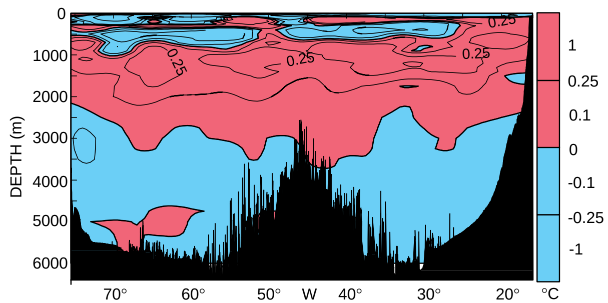
Temperatures between 1.5 and 2.5 km depth near Bermuda show an increase of 0.4°C over the past 70 years. (T. Joyce, USA)

Where there are, for example from comparisons of WOCE observations with previous measurements, we see significant long–term changes. These changes are almost as large as those at the surface, have significant vertical extent and are seen across whole ocean basins. A test of coupled ocean/atmosphere climate models is whether they can reproduce these subsurface changes.

Measuring the slow movement of subsurface anomalies is difficult by measuring currents directly. WOCE uses temperature, salinity and tracer chemicals, e.g. CFCs, to show the time since water was last in contact with the atmosphere. The measurements reveal the path the water has taken around the ocean. Such information is important in assessing the ocean's ability to store greenhouse gases like CO_2.



CFC tracers show the time taken for deep water from near Greenland to move into the South Atlantic. (W. Smethie, USA)



A section from America to Africa (24°N) showing that temperatures increased by up to 0.5°C from 1957 to 1992, at depths between 1 and 2.5 km. (G. Parrilla, Spain)

Future Ocean Monitoring

‘Using WOCE experience to design a cost–effective ocean monitoring system’

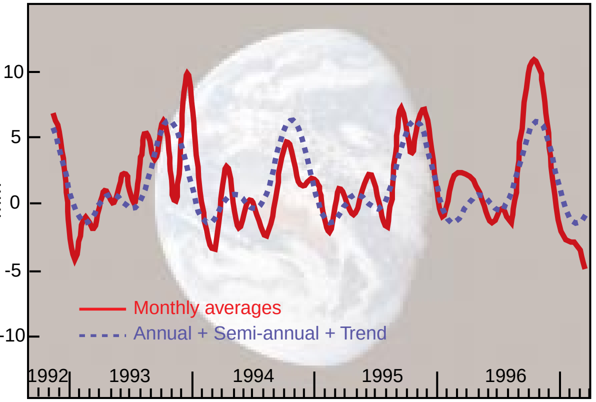
Research techniques and facilities have been used to make WOCE measurements but in the future, monitoring the ocean and its interaction with the atmosphere will require routine and more cost-effective methods.

Because of their global coverage, satellites measuring sea surface temperature, surface winds and sea–level are essential components of a long–term global observing system. However, in-situ observations will continue to be needed for calibration of satellite data.

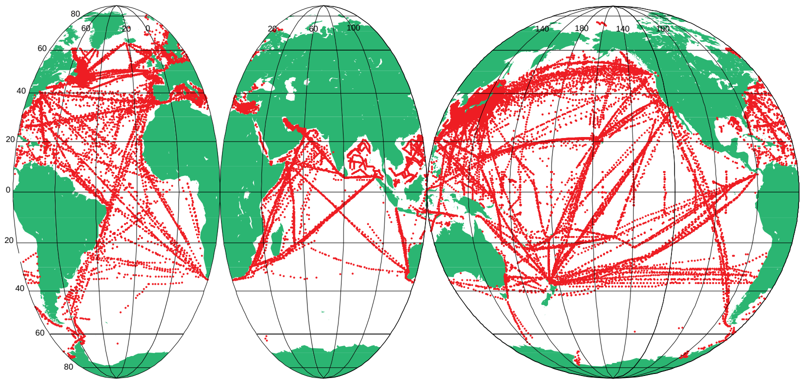
Routine subsurface measurements of the upper ocean can be made from merchant ships along major shipping routes. ALACE floats developed during WOCE can be used in all parts of the ocean to obtain temperature/salinity profiles. In the future acoustic remote sensing of the ocean interior may become routine.

Research ships and other research techniques will be essential complementary components for observing the global ocean in the future.

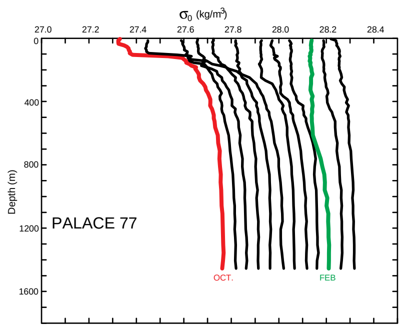
Assimilation of the observations into ocean models, as planned for the WOCE AIMS phase, is a key component in a cost-effective observing system, such as the planned operational Global Ocean Observing System (GOOS).



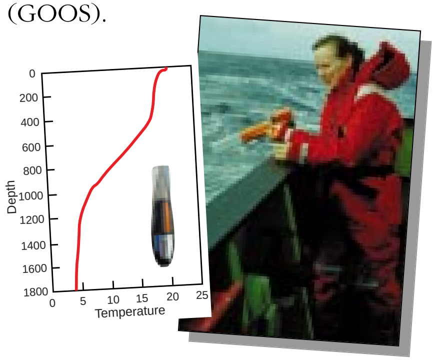
Global sea–level from TOPEX/POSEIDON and a fitted annual and semi–annual signal. (NASA, USA)



Distribution of upper ocean temperature profiles. There are few merchant ship observations in the Southern Ocean. (NODC, USA)



High latitude data from a profiling ALACE float show the winter changes in density structure caused by surface cooling. (J. Gould, UK)



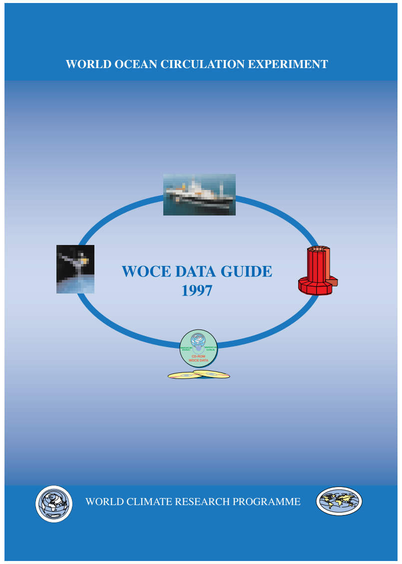
The WOCE Data Set – A Unique Resource

'A global data set of unprecedented scope, accuracy and quality'

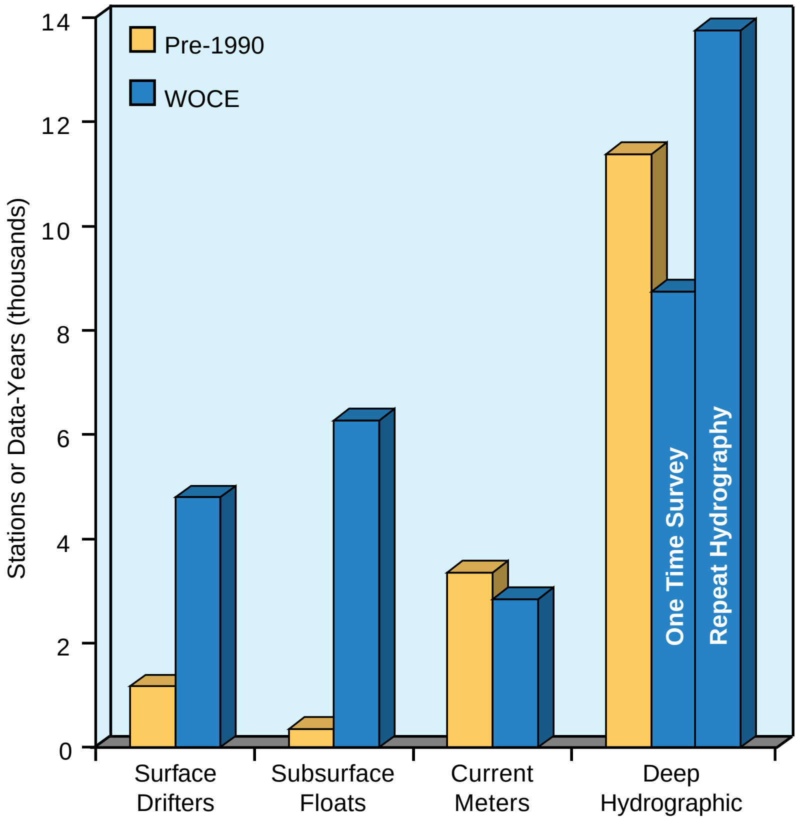
WOCE has generated a large, global and varied coherent data set which has dramatically enhanced the deep ocean data resource. The WOCE data system acquires and distributes high–quality, well–documented data, ensuring widespread usage. This is done through a network of Data Assembly Centres (DACs).

Each WOCE DAC has expertise in, and responsibility for, a specific data type. The centres receive and quality–control data from investigators. They also generate data products. The data and products are distributed via the Internet and on CD–ROMs to users ranging from students to leading research groups.

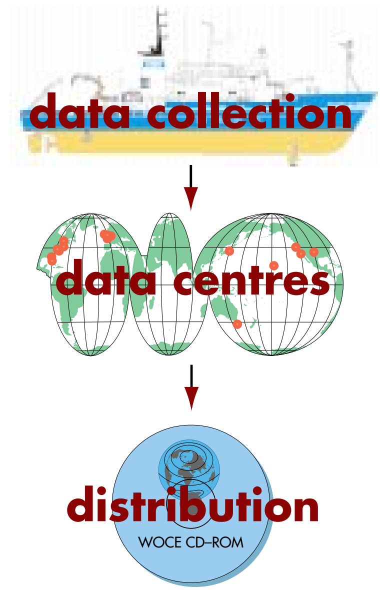
While WOCE data are now available from the DACs, it is planned that all WOCE in–situ data will be available by 2002 from the World Data Centre A (Oceanography) in Washington, DC, USA. The satellite data sets are handled by the satellite mission agencies.



Available from WOCE IPO



Comparison of amounts of data collected during WOCE and pre–1990 data held by US–NODC. (WOCE IPO)

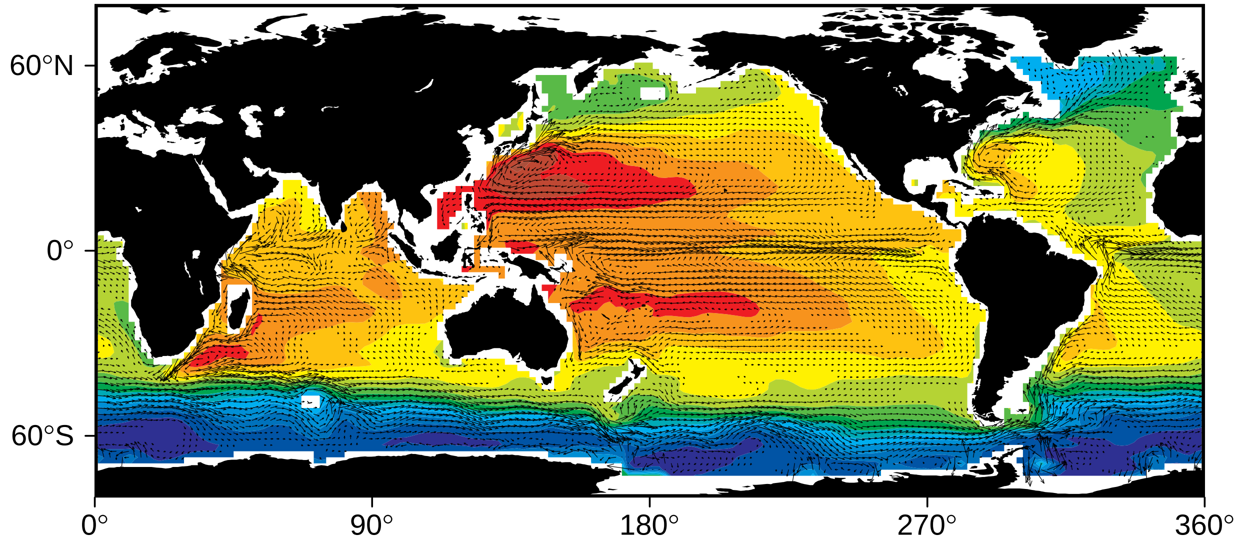


What has been Achieved? What Remains to be Done?

'Data assimilation is the key to defining the state of the ocean'

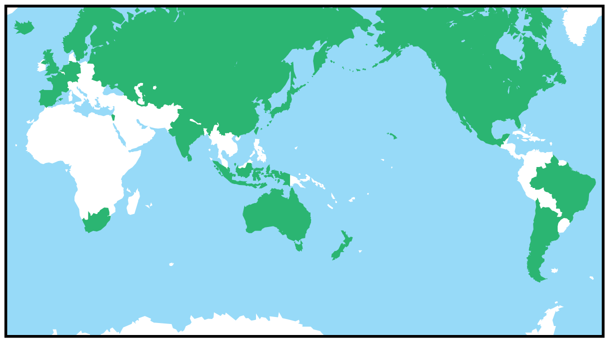
WOCE has been an enormous co–operative venture among marine scientists. It has carried out a large part of all components identified in the 1987 Implementation Plan.

Between $350m and $500m has already been spent on WOCE even excluding the costs of the satellites. This initial investment has already produced a unique data set as well as new and important results, some of which are displayed in this brochure.



The global surface circulation from assimilating satellite altimeter data into an ocean model (D. Stammer, USA)

WOCE scientists are co–operating through a series of regional and global work-shops. They initiate joint data analysis and inter–pretation and comparisons of models and observations.



Countries involved in WOCE

The greatest benefits from WOCE are yet to come. These benefits will result from model develop-ment, model–data intercom-parisons and assimilation of data into models. Ocean obser–vations will continue beyond 1997 in the WCRP Climate Variability and Predictability (CLIVAR) project and ultimately in an operational sense in the Global Ocean Observing System (GOOS).

CLIVAR and GOOS will draw on WOCE results. It is there–fore imperative that funding for WOCE AIMS activities continue until the project's end in 2002.