1.3

The Origins, Development and Conduct of WOCE

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1.3.1 Introduction

The late 1970s saw the end of a decade or more of experimental and analytical studies of the eddy field in limited parts of the deep ocean (Robinson, 1983). Numerical models, bounded by the power of available computers, were probing in similarly limited regions of the ocean basins. We were excited about what was being learnt and could see all manner of questions that needed to be addressed about the physical processes. Satellite altimetry was beginning to make an impact. There were more than enough questions of importance to keep us going in our traditional individualistic way, interspersed with the occasional grand expedition. However, there was a groundswell in the 1970s, both within and outside the community, that we should be paying more attention to the relevance of our work to the world at large. (Smaller-scale processes such as surface wave research had made this transition much earlier, supported by an already perceived practical need and by largely classical fluid dynamics.) Though there were other important strands of enquiry of practical interest, a growing concern for the global impact of climate change presented a remarkable opportunity for a refocusing of large-scale research towards global scientific problems.

In this chapter we attempt to describe in a personal, partial and informal way the evolution of a great experiment that, through a haze of (necessary) acronyms and some bureaucracy, emerges as it was started, as a sustained and we believe successful joint endeavour by many laboratories and individual scientists from many nations.

1.3.2 Large-scale oceanography in the 1960s and 1970s

At the start of the 1960s, the evidence for an active dynamical deep ocean was just emerging following the year-long observations made by the *Aries* expedition in 1959–60 in a small area of the western Atlantic. Previously the notion of a sluggish deep ocean had prevailed, primarily through the lack of direct current observations. Indeed, the original plans for the expedition, by Swallow and Stommel, envisaged the tracking of the newly developed Swallow floats individually for up to a year in the very local area.

Analytical studies of linear large-scale ocean circulation problems (gyre circulation, westward intensification, thermohaline circulation) had perhaps proceeded faster, uninhibited by observational knowledge of the pervasive eddy field.

In the 1960s, the community was gearing itself up with the new instrumentation needed to explore the picture tentatively being revealed of an eddy-populated deep ocean. Moored long-term current meters were designed in Europe and North America. Conductivity-Temperature-Depth (CTD) probes of potentially high accuracy were also being tried at sea. At the 1969 Joint Oceanographic Assembly in Moscow, there was a prediction that we were entering a decade of 'automated unreliability' as

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new technologies replaced the tried-and-tested traditional methods. There turned out to be some truth in this, but confidence was building sufficiently for some in the community to embark on a series of experiments in the 1970s, which eventually led to WOCE.

In 1970, Soviet scientists carried out POLYGON-70 (POLYGON meaning 'Training Field') in the subtropical northeastern Atlantic using arrays of moored current meters and CTDs. In 1971–74, the Mid-Ocean Dynamics Experiment (MODE) was a concerted attack on the dynamical description of the full-depth open ocean at the mesoscale. MODE (MODE Group, 1978) was an important stepping stone scientifically, technically and managerially.

Scientifically, the MODE core experiment over several months in spring 1973 concentrated on a patch of the Atlantic. It was centred on 28°N 71°W, measured 4° on the side, and was partly over rough and partly over smooth topography. It was not far from the *Aries* site. The experimental area was big enough that within the duration of the experiment the velocity and density fields could be intensively studied during the passage and evolution of an eddy.

Technically, new observational tools were available. Deep-drifting neutrally buoyant SOFAR (SOund Fixing And Ranging) floats, CTDs and moored current meter arrays, while still subject to frustrating failure, were matched in accuracy to the nature and scale of the phenomenon. The ships were fitted with the new, rapidly improving Transit satellite navigation system. (Oceanographers have been, and continue to be, among the leaders in exploiting the last iota of available accuracy from navigational systems.)

Managerially, MODE was a largely successful experiment in giving the responsibility for detailed planning to a scientific council of investigators from the participating institutions. The International Geophysical Year (IGY) in 1957–58 had been a major collaborative programme but had not required the extraordinarily close working relationship that developed on a day-to-day basis between the participating laboratories. MODE, US-led but with participation also from the UK, was a foretaste of new ways of working. For the first time modellers participated actively in a field programme's design and execution, and also studied the impact of equipment failure on the value of the results. This dialogue between observers and modellers, though sometimes fraught, has had a lasting and beneficial impact on the way large-scale oceanographic studies have developed.

Following MODE, a series of POLYMODE experiments in the North Atlantic by US and Soviet scientists established the pervasiveness, spatial variability and probable importance of the eddy field in the transfer of properties (Collins and Heinmiller, 1989).

1.3.3 Ocean research and climate

The meteorological community, under International Council of Scientific Unions (ICSU) and World Meteorological Organization (WMO) auspices, had established in 1966 the Global Atmospheric Research Programme (GARP) with two basic objectives:

- to improve the predictability of weather out to several weeks; and
- to understand better the physical basis of climate.

The first of these objectives dominated the planning and fieldwork in the 1970s. In consequence, the meteorological interest in the ocean in the First GARP Global Experiment (FGGE) was in large part limited to the reporting of sea surface temperature and pressure, these being the parameters of greatest importance for work on weather prediction. A positive outcome, which greatly influenced later WOCE planning, was increased interest in the use of drifting buoys as sensor platforms. Drogues on the buoys slowed their wind-induced drift and thus allowed, as an oceanographic bonus, estimates to be made of surface currents. The French *EOLE* satellite system was used in early experiments and later drifters used in the Southern Ocean during FGGE were the earliest large-scale operational use of random access satellite telemetry and buoy location techniques through the TIROS-n satellite. They provided essential surface meteorological coverage in an otherwise data-sparse region. The technique is now embodied in the commercial ARGOS location and data transmission system used today. The use of the ARGOS system with the profiling Autonomous Lagrangian Circulation Explorer (P-ALACE) floats (Davis and Zenk, Chapter 3.3) in the later years of WOCE is transforming the ability of oceanographers to collect synoptic subsurface data on the large scale.

1.3.3.1 The build-up to WOCE – Scientific Committee on Oceanic Research (SCOR) initiatives

Although the emphasis at the time of FGGE was on the first objective of GARP, oceanographers were starting to draw attention to the role that the oceans have in climate prediction. Interaction between oceanographers and the Joint Organizing Committee (JOC) of GARP intensified in early 1973. They saw the opportunities that the global network being developed for FGGE presented for extending knowledge, at least of the near-surface layers of the ocean. The Scientific Committee on Oceanographic Research (SCOR), through its Working Groups, played a key role in these international developments. One in particular, Working Group 43, chaired by Gerold Siedler, on 'Oceanography Related to GATE' (GARP Atlantic Tropical Experiment, our first encounter in oceanography with a second-order acronym!) was the first to develop and oversee an international oceanographic field programme within a major meteorological experiment. The scales of the design broadly spanned the synoptic scales in the atmosphere and the ocean. The oceanographic component (Düing, 1980; Siedler and Woods, 1980) was importantly the first significant step towards cooperative studies of the effect of ocean processes on climate. A meeting of the SCOR Executive Committee in 1974 in Canberra led to a significant rearrangement of SCOR's Working Groups that reflected the developing importance of climate questions. WG34 under Allan Robinson became 'Internal Dynamics of the Ocean', which was to become the focus of general ocean circulation modelling concerns. WG47 under Henry Stommel on 'Oceanographic Activities in FGGE' exploited the opportunities for oceanographic research, and WG48 directly addressed 'The Influence of Ocean on Climate'.

Discussions in Stommel's group led to the establishment in 1976 of the Committee on Oceanography and GARP (COG), which was to 'identify, stimulate and coordinate international programmes linked to the activities of GARP'. COG recognized immediately that the breadth of the problems related to climate change and variability included time scales longer than those with which GARP was concerned. Also at this time, WG48 (consisting de facto of the Chairman, Henry Charnock, and the JOC past Chairman, Bob Stewart) was also expressing the view that the problem of climate research went well beyond the objectives of GARP and that 'perhaps a major new initiative by ICSU was required'.

By 1977, the President of SCOR was writing to the Secretary-General of WMO, drawing attention to the need to consider the impact of ocean variability on climate as well as the atmosphere's impact on the ocean. With such an expanded horizon, it was appropriate for SCOR to join in the planning of the proposed 1979 World Conference on Climate Change and Variability. At this time, SCOR WG47 was proposing to COG a major field experiment in equatorial dynamics over at least 2 years, and also suggesting that it might be an opportunity for oceanographers to invite meteorologists to take part in a predominately oceanographic experiment.

By the mid-1970s, sufficient momentum existed within both the scientific community and the international organizations that sponsored and promoted their activities to launch an investigation of the ocean's impact on climate. Studies began of the observational systems that would be required for monitoring and prediction of climate variability on time scales from weeks to decades. SCOR, JOC, the Intergovernmental Oceanographic Commission (IOC) and WMO were all involved through the creation of panels and task teams and the holding of conferences to study various aspects of the problem.

1.3.3.2 The planning for WOCE – Committee on Climatic Changes and the Ocean (CCCO) initiatives

In 1978, WMO and IOC asked their scientific advisory bodies JOC and SCOR to convene a specialist meeting on the 'Role of the Ocean in the Global Heat Budget' to consider:

- a USSR proposal for a research programme looking into the processes of air–sea interaction for the purpose of developing long-term weather and climate theory. The programme would focus on Energetically Active Zones (EAZOs); and
- scientific problems related to extended range forecasting and climate.

The meeting, chaired by Bob Stewart, and held in Kiel, actually discussed four main topics:

- ocean circulation and heat transport;
- the USSR proposal (also known as SECTIONS);

- a Pilot Ocean Monitoring Study (POMS); and
- a proposed conference on the impact of climate on global change.

The latter eventually became the JSC/CCCO Study Conference on Large Scale Oceanographic Experiments in the WCRP, which was held in Tokyo in May 1982, with Allan Robinson in the chair.

Taking its lead from COG and adopting an even wider view, SCOR decided, in November 1978, to establish an interdisciplinary Committee on Climatic Change and the Oceans with Roger Revelle as chairman and invited the IOC to co-sponsor the committee. This the IOC agreed to do early in 1979. Meanwhile, WMO and JOC were reaching a similar conclusion; that an international mechanism was needed to determine to what extent climate could be predicted and the extent of anthropogenic influence on climate. The mechanism was to be the World Climate Research Programme (WCRP), co-sponsored by WMO and ICSU and dealing with time scales from several weeks to decades. The agreement to establish the WCRP was signed by WMO and ICSU in October and November 1979, and included the establishment of the Joint Scientific Committee (JSC) to oversee the programme. This, in effect, metamorphosed GARP into the WCRP.

By the end of 1979, the ocean community considered the situation very promising for the development of the oceanographic aspects of the WCRP. There was widespread interest in the large-scale circulation of the ocean. At a critical meeting in Miami in November to consider a Pilot Ocean Monitoring Study, Carl Wunsch made a convincing scientific case for a global ocean circulation experiment. The meeting proposed moving forward with the development of observational techniques and the design of networks, while simultaneously considering the feasibility and design of global experiments. This was a bold decision, relying on significant improvements in satellite sensors. The recently flown (1978) SEASAT mission gave grounds for optimism since in its short life it had demonstrated a much-improved precision in altimeter measurement of sea surface topography. The year-on-year trend of increasing computer power provided justification for expectation that the very large computer resources needed for eddy-resolving ocean models would soon be available.

The first meeting of CCCO was held immediately following the POMS meeting, also in Miami. That meeting asked the CCCO panel on 'Theory and Modelling of Ocean Dynamics Relating to Problems of Climate Research' and the CCCO/JSC Liaison Panel to take the lead on a global ocean circulation experiment (soon to be dubbed WOCE). It was the latter that moved the WOCE concept through the international scientific coordination bodies during 1980 and early 1981.

As well as paving the way for the development of WOCE, the Panel, following suggestions from the POMS meeting, instituted the CAGE feasibility study under the leadership of Fred Dobson (Dobson *et al.*, 1982). This was to consider the feasibility of a detailed study of the heat budget in a 'cage' over and in the North Atlantic ocean on a climatological time scale aiming for an estimate of oceanic meridional heat transport with an accuracy of 20%. The report provides valuable insights into the problems involved in the direct measurement of the transport, in estimates made through combination of inward radiation and flux divergence in the atmosphere, and those from area integrals of the sea surface heat flux.

Over the period 1979–81 CCCO had before it proposals for CAGE, WOCE and the Soviet SECTIONS Programme. Each would, if they could be implemented in full, entrain the resource of many laboratories. SECTIONS, though strongly pressed by Soviet scientists at meetings, did not find favour with the rest of the community. The programme assumed a concentration on a number of areas known as 'energetically active zones' such as the Gulf Stream and Greenland–Iceland–UK Gap. Other scientists believed that this intensive study of specific areas was unlikely to yield the scientific return to match the effort needed. CAGE, in the end, fell short of its overall goal through the inability to measure the horizontal fluxes across the atmospheric boundaries. Therefore, as a combined oceanographic and meteorological experiment it was felt to be premature. WOCE, on the other hand, subsumed much of the oceanographic thinking of CAGE and moved for the first time from a regional to a global view of ocean dynamics.

The significance of the POMS deliberations for the study and prediction of climate variability can be clearly recognized in the subsequent programmes that benefited from new and improved methods for measuring the ocean. WOCE and

TOGA (WCRP's Tropical Ocean Global Atmosphere Study) were the early beneficiaries but POMS also led to the Ocean Observing System Development Programme (OOSDP), organized for CCCO by Francis Bretherton, which addressed the wide range of oceanographic and atmospheric measurement systems that needed either reinforcement or design and development. The OOSDP (Intergovernmental Oceanographic Commission, 1984) was later turned into the JSC/CCCO OOSD Panel led by Worth Nowlin. The Panel produced a valuable series of scientific reports that led to a design for an ocean observing system for climate, more specifically the climate component of the Global Ocean Observing System (GOOS). Most recently, the Climate Variability and Predictability Study (CLIVAR) Implementation Plan (World Climate Research Programme, 1998) to some extent builds on the observing systems that became prominent during WOCE and TOGA and the proposals emanating from the OOSD Panel's report.

The expectation that new information over all (or large parts) of the ocean from satellites would be available by the late 1980s, meant that coordination of satellite missions was desirable and that the requirements of the oceanographic and meteorological communities should be taken into account. JSC and CCCO called a meeting in Chilton, UK, in January 1981 to identify how (with some adjustment to schedules, orbits and sensing capabilities) projected satellites could form an essential and complementary set of observing systems to the planned *in-situ* oceanographic experiments (World Climate Research Programme, 1981). The NASA, ESA and NASDA space agency participation (from the USA, Europe and Japan) ensured that they were aware of the scientific needs. The recommendations of the meeting were addressed immediately by the JSC and CCCO. Both gave priority to an altimeter with sub-decimetre accuracy, to determination of the geoid, and to scatterometer measurements of the surface wind field as well as identifying a host of other critical satellite coordination issues. CCCO considered that the 5-year mission duration suggested by the meeting was barely adequate to define the annual cycle in many parts of the ocean. They also noted that many important oceanographic phenomena had return intervals longer than 5 years. Hence they requested extended satellite coverage.

Michel Lefebvre (personal communication) recalls that, at Chilton, the US proposal was discussed for TOPEX, a satellite carrying an optimized sub-decimetre precision altimeter. Moreover, in January 1978, a European group meeting in Schloss-Elmau (European Space Agency, 1978) had proposed an altimeter mission to ESA. Neither proposal gained immediate acceptance from the agencies. The European proposal eventually became incorporated in the successful but less-optimized multisensor ERS missions, while TOPEX was in competition with wind measuring and to a lesser extent, geodetic missions. Both these missions would contribute valuably but TOPEX was pivotal to WOCE's success.

Later in 1981, French scientists won the approval of Centre National d'Études Spatiales (CNES), and strong ministerial support, for POSEIDON, an altimeter to be flown on the French SPOT satellite. SPOT also carried a new global tracking system DORIS dedicated to, and optimized for, altimetry using an onboard receiver and a worldwide network of 50 stations. It is extensively used also for gravity field improvement. The case for a dedicated altimeter mission to make a unique and vital contribution to WOCE was immensely strengthened as France and the USA in the succeeding years developed a joint proposal for a TOPEX/POSEIDON (T/P) satellite to be launched on a French Ariane rocket. It would carry US and French altimeters and tracking systems in an orbit precisely optimized for WOCE. The Memorandum of Understanding between the two countries, signed in 1987, envisaged laying the foundation for a follow-on after T/P (Michel Lefebvre, personal communication; Ratier, 1988).

In May 1981, CCCO established a WOCE Design Options Study Group chaired by Francis Bretherton. It was charged with reporting to JSC and CCCO (after presenting the preliminary plans to the Tokyo Conference on Large-Scale Oceanographic Experiments in the WCRP, in May 1982). Some significant points raised by CCCO were that:

- altimetry with simultaneous scatterometry was essential;
- variability of sea surface topography should be easier to measure and be of more significance for climate variability than the mean;
- many areas of the oceans needed to be covered with a network of surface to near-bottom

high-quality, complete modern hydrographic stations including temperature, salinity and nutrients; and

- appropriate methods for obtaining *in-situ* measurements of deep currents, needed for verification purposes, should be looked into.

Having heard the basic strategy for WOCE as formulated by the Design Options group, the 3rd meeting of CCCO in March 1982 offered these further observations:

- the importance of direct current measurements at the equator and over continental slopes;
- the importance of including global wind stress data;
- the advantage of combining satellite altimeter data with tide gauge data; and
- that deep-sea pressure gauges would be needed to support altimeter measurements.

The stage was now set for presentation of WOCE to a wider scientific community at the Tokyo conference (World Climate Research Programme, 1983).

The conference concluded that WOCE would be crucial for understanding the role of ocean circulation in the behaviour of the physical climate system and would be a major contribution to meeting the objectives of the WCRP. The conference recommended that the WCRP, JSC and CCCO create a Steering Group to review and guide the development of WOCE as a major activity within the WCRP. It was also recommended that the Steering Group, as a matter of priority, carry out detailed studies of such matters as:

- the appropriate mix of observing and assimilation systems needed to achieve the WOCE objectives;
- evaluation of the critical gaps of existing knowledge; and
- the actions needed to fill such gaps.

The conference pointed out that further specification of the required satellite systems (precision altimeters and scatterometers) was of particular urgency. Explicit requirements needed to be developed for forwarding to the various satellite agencies explaining:

- the desired and minimum accuracy needed;
- the desired orbital (sampling) parameters;
- the possible compromises stemming from a multinational but coordinated programme; and
- the value that would be gained by WOCE of having accuracy or sampling beyond the minimum levels needed (and up to the levels that were seen as desirable).

Finally, the notion of an experiment aimed at both the general circulation of the ocean and water mass transformation was welcomed by the conference and emphasized in the conference report. In particular, the list of observational foci of WOCE specifically refers to the determination of ventilation times and rate of water mass conversion. The discussions in Tokyo added to the list the need to make observations of the large-scale aspects of the seasonal cycle. This included the depth of the late-winter convective overturning and the study of broadband inherent variability.

In late 1982, the CCCO and JSC officers agreed, based on the Bretherton group report and the Tokyo conference conclusions and recommendations, to collaborate in establishing a WOCE Scientific Steering Group (SSG). Early in 1983, CCCO and JSC established the WOCE SSG and appointed Carl Wunsch as its chairman. WOCE had now become the principal oceanographic contribution to WCRP stream 3 on the prediction of decadal variations of climate.

1.3.4 Implementation of WOCE (SSG initiatives)

The first informal meeting of the WOCE SSG took place appropriately during a meeting on satellites at San Miniato, Italy, in April 1983, but the first formal meeting of the SSG was at Woods Hole in August that year. This immediately followed a US National Academy of Sciences Workshop on 'Global Observations and Understanding of the General Circulation of the Ocean' (National Academy of Sciences, 1983) at which Carl Wunsch presented an outline of WOCE (Wunsch, 1983).

The next 5 years were a period of intense activity, refining the scientific objectives through a series of workshops, and entraining the enthusiasm of both national funding authorities and scientists and producing both a Science Plan (World Climate Research Programme, 1986) and an Implementation Plan (World Climate Research Programme, 1988a,b). This planning phase culminated in the International WOCE Scientific Conference at the end of 1988 (World Climate

Research Programme, 1989a). Its purpose and achievement was to present the Implementation Plan to national authorities, to gain their interest, and to gauge their commitment. Thirty-one countries announced their intention to commit resources. By the end of the field phase, we could count the actual involvement of 22 countries, the contributions from which varied from more than 50% by the USA to small but valuable local contributions by small countries.

In this review we have chosen to pick out some highlights in the planning process that at the time were seen to be important, or in retrospect have become so.

The first three meetings of the SSG through early 1985 were critical in firmly establishing the objectives of the experiment and concluding that these could not be achieved by a generalized expansion of large-scale oceanography. This view was encapsulated eventually in the now much-repeated statement of the two goals of WOCE:

- To develop models useful for predicting climate change and to collect the data necessary to test them; and
- To determine the representativeness of the specific WOCE data sets for the long-term behaviour of the ocean, and to find methods for determining long-term changes in the ocean circulation.

This emphasis was not particularly limiting on the scope of the field programmes that would emerge. Indeed the initial WOCE working groups on surface forcing, reference level velocity, critical aspects of temperature/salinity distribution, tracer distributions and inputs, variations in diapcynal mixing, and depth of winter mixing read like a catalogue of problems in physical oceanography at the time. A careful reading of the WGs' terms of reference (SSG-1) is necessary to understand the focus provided by the WOCE goals. The working groups' reports contributed to a further refinement of goal 1 of WOCE to become:

To determine and understand:

- the large-scale fluxes of heat and fresh water and their divergences;
- the dynamic balance of the circulation and its response to changing surface fluxes;
- components of variability on months to years and megametres to global scale; and
- volume and location of water masses with ventilation times of 10–100 years.

The working groups were all, in one way or another, asked to pay close attention to the ability of existing measurement systems to meet the defined accuracy requirements. If such requirements could not be met, they were asked to consider if they could realistically be met by developing technology during the period of WOCE. The absolute priority for the success of the experiment was, to have at least one dedicated altimetric satellite mission, coincident with a global hydrographic survey of higher accuracy than ever before, of sufficient along-track resolution to avoid aliasing of the eddy field.

The TOPEX/POSEIDON satellite, while ultimately highly successful, provided anxious moments up to the time of launch when the durability of some of its batteries came into question. The SSG encouraged the launch of a geodetic satellite that would provide a greatly enhanced reference geoid to allow inference of the absolute topography of the sea surface. Coincidence in time was not a requirement, but the SSG foresaw the possibility of 'data decay' if the geoid and altimetry observations were too far separated in time. That satellite has yet to be launched. On the other hand, technical developments, some driven directly by the requirements of the programme, added greatly to the success of the experiment. The *in-situ* development with potentially the greatest direct impact on a global scale was the Autonomous Lagrangian Circulation Explorer (ALACE) programme of floats to measure the deep reference velocities and described elsewhere in this book (Davis and Zenk, Chapter 3.2). While RAFOS (reversed SOFAR) was building on the established SOFAR acoustic navigation technology for floats and would contribute greatly to the dynamical studies in the North and South Atlantic, ALACE was a developing technique. For ship-based velocity measurements, Global Positioning System (GPS) navigation and differential techniques permitted the hoped for, but in 1985 uncertain, development of Acoustic Doppler Current Profilers (ADCPs) as a valuable underway and on-station tool for the measurement of deep velocity profiles (King *et al.*, Chapter 3.1).

The Numerical Experimentation Group (NEG), befitting the central role of models in the project's goals, became the first of WOCE's 'permanent' working groups. From the beginning, a strategy was adopted that explored both inverse and direct models. At the time, in the mid-1980s, eddy-resolving models were evolving only at the basin scale though the NEG was predicting the availability of global eddy-resolving models soon after the end of the twentieth century. The wish for a detailed input by modellers into experimental design, first stated in MODE and reiterated in NEG's first report, remained elusive.

With the reports of the working groups available, the SSG identified three major components (Core Projects – CP) of the programme:

- CP1, the Global Description, provided the unified framework for a global set of *in-situ* and satellite observations to meet the first and last of the Goal 1 objectives;
- CP2, on Interocean exchanges (later limited to exchanges with the Southern Ocean), was set up in recognition of the distinct scientific and logistic problems of the Southern Ocean; and
- CP3, in which dynamical models would be built and tested against an intensive set of observations on a basin scale before applying the models to the global data set.

Week-long workshops were held during 1986 to complete the initial planning of the CPs. The workshops were well attended (about 50 scientists from 13 nations at CPs 1 and 2, and from nine nations at CP3).

The CP1 workshop reached a consensus as to what should be included in the global programme of measurements to meet WOCE objectives. Although they expected changes to details, they felt the scope of CP1 would remain unchanged throughout WOCE's lifetime. This has generally been proven true.

The CP2 workshop took advantage of earlier Southern Ocean studies and reviews such as SCOR's Working Group 74 report on 'The General Circulation of the Southern Ocean: Status and Recommendations for Research'. The Workshop focused on:

- Antarctic Circumpolar Current (ACC) dynamical balance and heat and mass transport;
- meridional transports through and out of the Southern Ocean; and air–sea–ice interaction.

The outcome of the discussions of these processes became the basis for the initial CP2 implementation plan.

The CP3 workshop was unable to complete many aspects of the planning. With the exception of studies of the deep circulation in the Brazil Basin, it was clear that there were many reasons for locating most of CP3 in the North Atlantic. The workshop examined processes in the surface layer, interior and within the deep circulation needing consideration and suggested some experiments. However, a problem existed with resources and with coordination that would last until the mid-1990s and the advent of the predominantly US Atlantic Climate Change Program (ACCP) (Whitburn, 1994).

The scope of the hydrographic programme as envisaged in CP1 and CP2, with their long transoceanic meridional and zonal sections and requirement for tracer observations, was clearly going to stretch the capabilities of existing research ships. Typically these ships were limited to cruises of 4 weeks duration and a scientific party of 20. The WOCE SSG for some time worked on the idea of a Research Vessel (RV) *WOCE*, a dedicated and internationally managed shipboard operation to accomplish these major sections. Eventually a less centralized approach prevailed by exploiting existing individual nationally managed resources coordinated by a WOCE Hydrographic Programme Planning Office (WHPO). Even so, major refits and lengthening of research ships took place to accommodate the scientific crews of 30 or more and cruise duration of 6 weeks that the WHP required. The Indian Ocean component of the WOCE programme in 1995 came closest to the RV *WOCE* concept with the successful use of a single US funded ship, RV *Knorr*, and technical support from a single group for the bulk of the sections.

WOCE took the integration of observations started with MODE and POLYMODE into a new era by drawing on a very wide range of techniques. Their great scope led to some important decisions, sometimes preceded by heated debate. This is typified by the decision to use a range of geochemical tracers, particularly those with time-dependent characteristics derived from radioactive decay or the variability of their source function. It was based on their expected utility in clarifying the pathways and circulation rates in the interior of the ocean. They were expected to extend greatly the level of understanding beyond that possible using only the traditional base of temperature, salinity and nutrient data. The resulting programme was perhaps less than a geochemist would have wished for but was an example of concentrating on the specific goals of WOCE. In the event, a major survey of CO_2 in the oceans was developed under the International Geosphere-Biosphere Programme's (IGBP) Joint Global Ocean Flux Study (JGOFS) with measurements on WOCE cruises (Wallace, Chapter 6.3).

From the start, it was recognized that the scale of the experiment and the likely level of resources would leave little room for redundancy in the observations if the objectives were to be achieved. This fact in itself led to a continuous critical evaluation of the data requirements of each component of the experiment. In retrospect this can be most clearly seen in Volume 2 of the Implementation Plan, in which the achievement of the scientific plans was linked to a series of largely non-redundant observations. At the time, there was some discussion whether Volume 2 was a useful part of the implementation plan, but it has served as a valuable tool in identifying critical observations.

George Needler, Director of the WOCE International Planning Office (IPO) for the important initial 4 years from 1985, led the writing of the Implementation Plan. The Plan was prepared over several months in early 1987 and engaged the resources of the IPO, SSG members (and other colleagues drafted in). Volume 1 gave the detailed description of the observations to be made, parameter by parameter, while Volume 2 linked the observations to the scientific objectives. An advantage of the presentation adopted in the Plan is that it is easier to identify the critical observations and to classify others, which, though important in some regional or other scientific context, as less important.

1.3.4.1 The Intergovernmental WOCE Panel (IWP)

During the planning phase, CCCO was a constant source of support, taking on much of the responsibility for keeping WMO, IOC and ICSU in touch with the experiment and resolving bureaucratic issues that arose. The implementation of the Law of the Sea and, in particular, the components of it relating to access to the Exclusive Economic Zones (EEZ), was of concern. Dynamically important boundary currents lay within such regions and there were a number of instances where access was difficult to negotiate or in some cases refused. It remains to be seen what impact this lack of access had on the data set and whether future programmes need be concerned.

Soon after the 1988 WOCE Conference, the IOC established the Intergovernmental WOCE Panel (IWP) to assist the WOCE community in meeting the scientific, managerial, implementation and resource needs of WOCE as defined by the SSG. The IWP's objectives were similar to those of the Panel that had been established by WMO for TOGA. At its three sessions between 1990 and 1995, IWP provided nations with another opportunity to make commitments to WOCE. Even though the scientific community through the efforts of CCCO and JSC and their sponsors and subsidiary bodies worked diligently to accommodate all potential WOCE participants, some nations still wanted coordination of their WOCE activities at the intergovernmental level. Each IWP meeting 'uncovered' some new resources and tended to force nations to be specific about their participation. Access to EEZs was discussed and, in at least one case, the IOC was successful in providing the mechanism through which rights were obtained. The IWP still exists and could be utilized if needed during the final phase of WOCE.

1.3.4.2 The data-sharing model developed by WOCE

Prior to WOCE, the principal international mechanism in place for exchange of data from research activities was that through the World Data Centre system. This had been created, in support of the International Geophysical Year (IGY), in 1958. Oceanography in particular had benefited through a long-term collaboration between national data centres to the extent that there was at least a major archive of hydrographic data. However there were, and are, major problems with that system when applied to specific programmes:

- submissions to the archive were delayed by many years;
- data were of varied and often unknown quality;
- only a small number of, mainly hydrographic, parameters were collected systematically; and
- national centres, with only a few exceptions, had not been committed to active data management for a project.

Roger Revelle (personal communication, 1982) commented that data management was one of the

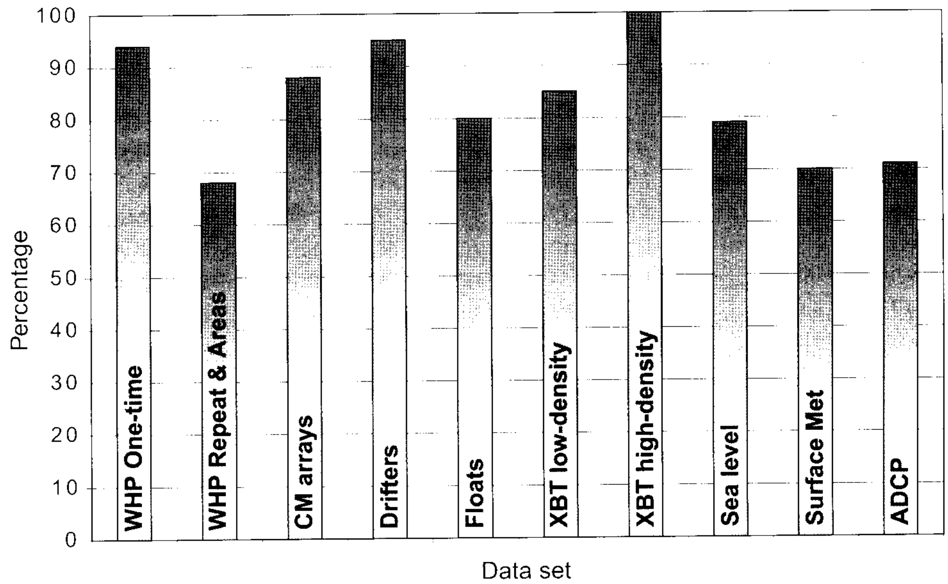

Fig. 1.3.1 Percentage of total data sets submitted to WOCE Data Assembly Centres, February 2000. WHP, WOCE Hydrographic Programme; CM, Current Meter; XBT, Expendable BathyThermograph; Surface Met, Surface Meteorology; ADCP, Acoustic Doppler Current Profilers.

most important problems facing both WOCE and TOGA and that researchers needed to ensure that it was done properly, even though the topic bored him to tears! So, in 1984 CCCO sponsored a meeting jointly with the IOC's Committees on International Oceanographic Data Exchange (IODE) and the Integrated Global Ocean Services System (IGOSS) to review and recommend the way forward. Shortly before, the US National Academy of Sciences, Space Studies Board, Committee on Data Management and Computation (National Research Council, 1982) had extensively reviewed the successes and failings of present and past satellite data management systems. It had identified some very general principles for success. The meeting felt these principles could easily be adapted to handle WCRP scientific data. They included active end-to-end involvement of scientists in the data acquisition and distribution process, peer review by the user community of the data management activities, data formats designed for ease of use by scientists, and metadata (ancillary information) to be available with each data set.

For WOCE, there was the added challenge of bringing together the data from three sources; satellite systems, ship-based research systems, and operational networks, each with its own mode of operation and time scale of data delivery. By 1986 the WOCE SSG had developed a plan based on these principles, which was to stand the test of time. Now (2000) it has demonstrably delivered (Fig. 1.3.1) to the scientific community an unprecedented set of high-quality data in a time frame not too different from that originally planned.

The WOCE Plan proposed seven Data Assembly Centres (or DACs) servising separate primary data sets and supervised for the most part by scientists in research laboratories that were intimately concerned with the field programme. They covered the hydrographic programme, current meters, floats, surface drifters, sea level, expendable bathythermographs (XBTs), and surface meteorology. ADCP, bathymetry and sea surface salinity centres were added some years later. In addition, further scientific involvement was envisaged through Special Analysis Centres (SACs), essentially a mechanism that would serve to disseminate and preserve the derived data products from research. Although two were established (surface fluxes and hydrography) it is only now, with the advent of operational programmes such as the Global Ocean Observing System (GOOS), that interest in similar centres is developing.

The supervision of WOCE data involved scientific as well as technical quality control by independent review. This was for the most part readily accepted and welcomed by the originating Principal Investigators (PIs) as part of a peer review process. For their part, PIs were asked to submit their data within the unprecedentedly short period of 2 years following the fieldwork. In some cases even a 6-month period was suggested – unrealistic perhaps at the time but now at the end of WOCE and the beginning of new field programmes not at all so. Such is the change of attitude that has been fostered.

The validity of the system is supported by three observations about the present situation:

- the unprecedented cooperation of scientists in submitting the data;
- most DACs are still largely run by the same scientists who established them; and
- the fact that the DACs have scrupulously safeguarded data submitted to them early while still allowing their use by agreement with co-workers.

'Data sharing' of new data has now gained widespread acceptability and hopefully will be the norm in future experiments. One finds in the WOCE bibliography, for example, no evidence of the plagiarism that some feared might result from early submissions of data to the DACs. The WOCE data system is described more fully by Lindstrom and Legler (Chapter 3.5).

There is a strong tendency in such a system for each component to go its own way so, in addition to the DACs, a Data Information Unit (DIU) was formed. Its function was to provide a single summary source on the progress of the experiment, the data and products available at the DACs, agreed standards and procedures, a bibliography, and generally to facilitate communications in WOCE. The system adapted well to the changing technology. Electronic mail was used from the very earliest planning phase of WOCE and indeed, it is hard to see how the planning process could have progressed so rapidly without it. By early 1994 the DIU was one of the first few hundred sites offering a world wide web connection, with the DACs following shortly after. The DIU's functions, too, have changed significantly from being an online source of the national and international plans for the experiment, to being a summary source for the progress of the experiment and for links to the data sets and DACs, and now support of the final phase of the experiment.

1.3.5 Implementation and oversight

The prospect of truly global oceanography was exciting and in consequence entrained the collaboration of a large proportion of scientists engaged in deep sea physical oceanography. Although the planning was carried out during the economic boom-years of the late 1980s, the start of WOCE observations in 1990 coincided with a global economic downturn followed shortly by the dissolution of the Soviet Union. This led to the curtailment of many of the repeated hydrographic sections. The first official WOCE cruise in January 1990 was the occupation of a section across the Drake Passage on F.S. *Meteor*.

As is often the case with satellites, the launch dates of the two that would provide the altimeter and scatterometer coverage required by WOCE slipped from their original dates. TOPEX/POSEIDON was launched in August 1992 (and remarkably continues 8 years later to provide excellent data well beyond its design life; Fu, Chapter 3.3). ERS-1 had been launched in July 1991 on a more general-purpose earth observation mission that included altimetry and scatterometry. ERS-1 has now been succeeded (in 1995) by an almost identical ERS-2.

The delay in satellite launches meant that the 5-year observational phase starting in 1990 would not allow a full 5 years of coincident high-precision satellite altimeter coverage. The SSG at its 15th meeting in Toulouse in October 1990 therefore agreed to 'extend the Global Survey over the period 1990–1997 (but no longer)'. In fact some WOCE hydrography continued into 1998.

A key new element in the WOCE observational strategy was the Autonomous Lagrangian Circulation Explorer (ALACE) float programme. The first significant deployment of ten floats was made in the Drake Passage on *Meteor*'s 1990 cruise. It was only as these floats progressed on their 2-week cycle that we learned about their performance and survival rates and found that they would indeed provide the global coverage WOCE required. These floats are described by Davis and Zenk (Chapter 3.2).

Through the observational phase, the WOCE IPO and the DIU played a key role in monitoring progress and highlighting potential problems. The International Planning Office provided administrative backup for all WOCE Panels and WGs and regularly promulgated information about the project through the WOCE International Newsletter. The DIU, together with the IPO (which became a Project rather than Planning Office in 1990), compiled annual resource assessments of the experiment. During this time the IPO was led, in succession, by Peter Koltermann (1989–91), Nick Fofonoff (1991–93), and John Gould (1993 to present).

By 1994 (just past the mid-point of the now-extended observational phase) it was clear that WOCE would need a more detailed strategy for its post-observational phase. In consequence, the SSG and IPO drew up a plan for a phase of Analysis, Interpretation, Modelling and Synthesis (WOCE AIMS). In March 1995, the JSC, having inherited the responsibility for WOCE from CCCO, endorsed the plan and agreed that WOCE should continue in its AIMS phase to 2002 (WOCE IPO, 1995). An integral part of the strategy was the streamlining of the WOCE oversight structure. Up to this time each Core Project and many programme elements had their own oversight Panel and modelling activities were by-and-large considered separately from observations and coordinated by the WOCE Numerical Experimentation Group (NEG). The Core Project Working Groups were therefore disbanded in favour of a Synthesis and Modelling WG (SMWG), bringing together observationalists and modellers. It first met in October 1995 to start the preparation of a detailed plan for the AIMS phase (WOCE IPO, 1997).

Additionally in 1997 the Data Products Committee (this had changed in 1994 from being a Data Management Committee) assumed oversight of the WOCE Hydrographic Programme.

An essential element of the WOCE AIMS strategy was a series of regional and subject-based workshops that would (in the case of the regional meetings) stimulate basin-wide syntheses of WOCE data sets and foster collaboration between research groups. The first of these workshops was held in 1996 on the Pacific Ocean. The complete sequence and locations is shown in Table 1.3.1.

Table 1.3.1 Sequence of WOCE AIMS phase workshops

Subject	Venue	Date
Pacific Ocean	USA	August 1996
South Atlantic	France	June 1997
Southern Ocean	Australia	July 1997
Ocean state estimation (with GODAE[a])	USA	March 1998
Ocean modelling (with CLIVAR)	USA	August 1998
Indian Ocean	USA	September 1998
Tracer AIMS	Germany	February 1999
North Atlantic	Germany	August 1999
Ocean variability (with CLIVAR)	Japan	October 2000
Global transports (with JGOFS)	UK	Summer 2001

[a] GODAE – Global Ocean Data Assimilation Experiment

A significant number of papers based on science presented at the regional workshops were published in special issues of the *Journal of Geophysical Research*. The reports of the workshops have been published by the IPO and in a number of cases these reports contain recommendations that are of long-term consequence. For instance the Ocean Moelling workshop led to the re-formation of a group charged with stimulating ocean model development within the wider framework of the WCRP. The 2001 workshop on Global Transports will address a central objective of WOCE – that of determining the oceanic transports of heat and fresh water. The JGOFS CO_2 measurements made on the WOCE one-time sections will provide estimates of the CO_2 fluxes and a key inventory of CO_2 in the oceans (Wallace, Chapter 6.3).

A further activity of the AIMS phase will be the publication of a series of atlases of WOCE Hydrographic Programme One-Time Survey data in a common format embodying profiles of all the WHP parameters.

WOCE held a conference on 'Ocean Circulation and Climate' in Halifax, Nova Scotia, Canada, in May 1998 to mark the end of the observational phase, to review the state of WOCE science and to give the large WOCE community an opportunity to make poster presentations of their latest results. The attendance of almost 400 ranging in age from the founders of WOCE to students who had barely started school in the late 1970s was gratifying and the keynote presentations were the starting point for this book. The 1998 conference was also the occasion of the distribution of the first set of WOCE Global Data on CD-ROMs. Preliminary planning is now underway for a final WOCE Science Conference to be held in the USA in 2002.

1.3.6 Was WOCE a success and what is its legacy?

WOCE achieved much of what it set out to do in terms of making ocean observations and, of those data, a large proportion are already available to the scientific community. WOCE required an unprecedented level of international collaboration that was readily forthcoming, perhaps because of the remarkable challenge that WOCE presented and the unique opportunity that it provided. It was helped by the fact that by-and-large it involved a single discipline, physical oceanography of the open ocean. It did require a close interaction of seagoing oceanographers, scientists concerned with the ocean–atmosphere interface, ocean modellers and satellite remote-sensing scientists. One might argue that it took a while for each subgroup to appreciate the others' abilities. In the mid-1990s modellers were often being asked for guidance by the observationalists as to what measurements and fields were required to critically test the models. Only in 1998 at the Ocean Modelling workshop were the modellers sufficiently confident to start to address these questions. The advances in computer power have meant that while in 1980, when WOCE planning started, global ocean models were running at a resolution of 2°, 20 years later global models are running at 1/8° resolution and their representation of the ocean is becoming increasingly realistic. However, progress towards the objective of the four-dimensional data assimilation of ocean data into such models to provide ocean state estimations remains computer resource limited.

Some aspects of WOCE proved too complex and required too much coordination to be achieved. This was notably true of the CP3, the Gyre Dynamics Experiment. As originally planned it sought to observe the response of the gyre-scale circulation to the changing forcing field by means of repeated occupations of so-called Control Volumes (arrays of eddy-resolving hydro stations covering significant sectors of the Northern Atlantic Gyre), following the example set by the analysis of the beta triangle (Armi and Stommel, 1983). These proved too complex and required too heavy a ship commitment to be achieved by WOCE. However, the conclusion of the field programme in 1998 was marked by a gyre-scale programme in the North Atlantic in which ship-based hydrography was complemented with extensive deployments of profiling ALACE floats.

Satellite remote sensing has demonstrated, through WOCE, its crucial role in almost all aspects of present-day marine science. Comparison of computer models with ocean data is now starting to reveal hitherto undetected aspects of the oceans' behaviour. The global synthesis and the assimilation of the data into models to provide an ocean state estimate for the 1990s is underway and it is only when this has been carried out that we will really know whether our sampling strategy was appropriate to address WOCE's goals. Undoubtedly the WOCE data set is one of unprecedented accuracy, geographical extent and comprehensiveness.

A measure of success for any scientific programme is the number of papers based on its results that appear in the refereed literature. The WOCE IPO maintains a bibliography and to date, even though systematic analysis of WOCE data has barely started, over 1200 refereed papers are indexed as being associated with WOCE results at the end of 2000; this number is now increasing at the rate of around 200 papers per annum.

WOCE leaves an important legacy to future programmes, whether they be associated with climate research, as is the case of CLIVAR; need a basic physical underpinning, as with the IGBP's GLOBEC (Global Ocean Ecosystem Dynamics) programme; or are part of the developing movement towards operational programmes, such as GOOS and GCOS (Global Climate Observing System). One might justifiably claim that through WOCE the study of the global ocean 'came of age' and that through WOCE we have (or will have) both the tools and the understanding to address global ocean issues such as climate change that are of huge socioeconomic importance.

Acknowledgement and sources

We are most grateful to Bob Stewart for making available the typescript of his talk at the WOCE Conference, Halifax 1998, and also for additional critical comments.

Some detailed references are included but the majority of our sources are from the meeting reports and serial publications of the organizations referred to in the text. Specific meetings are referenced as, for example, WOCE-1 for the first meeting of the WOCE SSG. For an early discussion of the scientific basis of the Experiment, see Woods (1985a).