Hydrographic Atlas of the World Ocean Circulation Experiment (WOCE)

Volume 3: Atlantic Ocean

Klaus Peter Koltermann, Viktor Gouretski and Kai Jancke

Bundesamt für Seeschifffahrt und Hydrographie,
Hamburg, Germany

Series edited by Michael Sparrow, Piers Chapman and John Gould

WOCE
WORLD OCEAN CIRCULATION EXPERIMENT

UH

Federal Ministry
of Education
and Research

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HELMHOLTZ
GEMEINSCHAFT

AWI

ГЕОГРАФИЧЕСКИЙ ФАКУЛЬТЕТ
МГУ имени М.В. Ломоносова

WCRP
World Climate Research Programme

World
Meteorological
Organization
Weather • Climate • Water

IOC

ICSU
International Council for Science

Hydrographic Atlas of the World Ocean Circulation Experiment (WOCE)
Volume 3: Atlantic Ocean

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Series edited by Michael Sparrow, Piers Chapman and John Gould.

Compilation funded by German Bundesministerium für Forschung und Technologie, BMFT.

Publication supported by BP.

Cover Picture:
The photo on the front cover was kindly supplied by Olaf Boebel. It was taken in mid December 1992, during the Meteor 22/4 cruise in the South Atlantic.

Cover design:
Signature Design in association with the atlas editors, Principal Investigators and BP.

Printed by:
Nauchnyi Mir Publishers, Moscow, Russia

DVD production:
Reel Picture, San Deigo, CA

Published by:
National Oceanography Centre, Southampton, UK.

Recommended form of citation:

1. For this volume:
Koltermann, K.P., V.V. Gouretski and K. Jancke. Hydrographic Atlas of the World Ocean Circulation Experiment (WOCE). Volume 3: Atlantic Ocean (eds. M. Sparrow, P. Chapman and J. Gould). International WOCE Project Office, Southampton, UK, ISBN 090417557X. 2011

2. For the whole series:
Sparrow, M., P. Chapman, J. Gould (eds.), The World Ocean Circulation Experiment (WOCE) Hydrographic Atlas Series (4 volumes), International WOCE Project Office, Southampton, UK, 2005-2011.

WOCE was a project of the World Climate Research Programme (WCRP) which is sponsored by the World Meteorological Organization (WMO), the International Council for Science (ICSU) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

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500 m	178	178	179	179	180	180	181
1000 m	182	182	183	183	184	184	185
1500 m	186	186	187	187	188	188	189
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Isopycnal Maps

	Depth (m)	Potential Temperature (°C)	Salinity (PSS78)	Oxygen (μmol/kg)	Nitrate, Nitrate+Nitrite (μmol/kg)	Phosphate (μmol/kg)	Silica (μmol/kg)
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27.22 kg/m^3	206	206	207	207	208	208	209
27.95 kg/m^3	210	210	211	211	212	212	213
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FOREWORDS

WCRP
World Climate Research Programme

The World Ocean Circulation Experiment (WOCE) was the first project of the World Climate Research Programme. It focused on improving our understanding of the central role of the ocean circulation in Earth's climate system. Its planning, observational and analysis phases spanned two decades (1982-2002) and, by all measures, WOCE was a very ambitious, comprehensive and successful project.

Throughout the 1980s, WOCE was planned to collect *in situ* data from seagoing campaigns, robotic instruments and from a new generation of Earth observing satellites, and to use these observations to understand key ocean processes for improving and validating models of the global ocean circulation and climate system. A central element of WOCE was its Hydrographic Programme (WHP) that occupied over 23,000 hydrographic stations on 440 separate cruises between 1990 and 1998 to complete an unprecedented survey of the oceans' physical and chemical properties The WHP also collaborated with the International Geosphere-Biosphere Programme's Joint Global Ocean Flux Project (JGOFS) to measure key elements of the oceans' carbon chemistry.

WOCE results are documented in over 1800 refereed scientific publications and it is most commendable that the WOCE data sets have been publicly available via the World Wide Web and on CD ROMs since 1998, and DVDs since 2002. WOCE's scientific legacy includes: significantly improved ocean observational techniques (both *in situ* and satellite-borne) that became the foundation of the Global Ocean Observing System; a first quantitative assessment of the ocean circulation's role in climate; improved understanding of physical processes in the ocean; and improved ocean models for use in weather and ocean forecasting and climate studies. The WOCE Hydrographic Programme was of previously unimaginable scope and quality and provides the baseline against which future and pre-WOCE changes in the ocean can be assessed.

WOCE opened a new era of ocean exploration. It revolutionised our ability to observe the oceans and mobilized a generation of ocean scientists to address global issues. We now have both the tools and the determination to make further progress on defining the ocean's role in climate and in addressing aspects of global and regional climate and sea-level variability and change. However, much more remains to be done in the exploitation of WOCE observations and in the further development of schemes to assimilate data into ocean models. These aspects of ocean research and model development are now being continued in the Climate Variability and Predictability (CLIVAR) project, designed in part as the natural successor of WOCE and of the 1985-1994 Tropical Ocean Global Atmosphere (TOGA) project within the World Climate Research Programme.

I am delighted to introduce this, the third volume, in the four-volume series of WOCE atlases describing the WHP data set in the Atlantic Ocean. The volumes (and the science that has resulted from these observations) are a fitting testament to the months spent at sea and in the laboratory by literally hundreds of scientists, technicians and ships' officers and crew in collecting and manipulating these data into the much needed, valuable and timely resource that they represent. On behalf of all past, present and future users of these observations and the entire WCRP network of researchers, I thank them, the authors, editors and the sponsors of these atlases for their leadership and support throughout the years.

Ghassem R Asrar
Geneva, Switzerland

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bp

BP is proud to support the publication of the World Ocean Circulation Experiment (WOCE) Atlas series. These volumes are the product of a truly international effort to survey and make oceanographic measurements of the world's oceans.

When we consider that almost three-quarters of the Earth's surface is covered by ocean, it follows that this resource can be used as a crucial indicator of the world's well-being. As a result, any observed variation in ocean pattern and behaviour can potentially be an important indicator of change in climate. Around the globe, we are witnessing key alterations to our environment at an unprecedented rate. This includes sea-level rise, increased intensity of storms, changes in ocean productivity and resource availability, disruption of seasonal weather patterns, loss of sea ice and altered freshwater supply and quality.

In 1997, BP was one of the first companies in the oil and gas industry to accept the fact that, while the scientific understanding of climate change and the impact of greenhouse gases is still emerging, precautionary action was justified. BP became actively involved in the global climate change policy debate, supporting emerging technologies in relation to mitigation measures, and actively reducing emissions from our operations and facilities.

BP believes that co-operation in marine science can be of mutual benefit to all stakeholders and hopes that by sponsoring this publication, the WOCE can help to inform those responsible for policy and management decisions related to oceans and climate change. BP continues to support the production of the WOCE Atlases and hopes that these will contribute to the enhancement of marine data and information and a wider understanding of the current state of the oceans.

Bob Dudley
Group Chief Executive, BP p.l.c.

BACKGROUND

The concept of a World Ocean Circulation Experiment (WOCE) originated in the late 1970s following the successful first use of satellite altimeters to monitor the ocean's sea surface topography (National Academy of Sciences, 1983). WOCE was incorporated into the World Climate Research Programme (WCRP) as a means of providing the oceanic data necessary to test and improve models of the global climate, with a view to improving our knowledge of climate change (Thompson, Crease and Gould, 2001). The initial meetings to define WOCE were held in the early 1980s and, with planning complete, culminated in a meeting at UNESCO Headquarters in Paris, France, in December 1988 (WCRP, 1989). During this meeting representatives of many countries agreed to take part in the programme and pledged to carry out elements of the internationally agreed Implementation Plan (WCRP, 1988a,b, 1989). The hydrographic component, designed to obtain a suite of measurements throughout the global ocean, was the largest single part of the *in situ* programme.

A series of four atlases describes the results of the WOCE Hydrographic Programme (Orsi and Whitworth, 2005; Talley, 2007, 2011).This atlas is Volume 3 and focuses on the Atlantic Ocean and consists of a series of vertical sections of the scalar parameters measured during each of the WOCE One-time hydrographic survey cruises, together with a series of horizontal maps showing the geographical distribution of properties. These maps incorporate not only WOCE One-time data, but also high-quality pre-WOCE observations and data from the WOCE repeat hydrography programme. Finally, property-property plots of the parameters are presented for each line.

WOCE AND ITS OBSERVATIONS

The Hydrographic Programme was one part of the global sampling effort within WOCE, which also included satellite observations of the ocean surface, measurements of ocean currents using surface drifters, subsurface floats, current meter moorings, acoustic Doppler current profilers, measurements of sea level using sea level gauges, repeated surveys for temperature using expendable bathythermographs, and surface meteorology measurements (see Siedler, Church and Gould 2001). WOCE also supported major modelling projects, including both general circulation models of both the ocean alone and of the ocean coupled with the atmosphere, and ocean data assimilation activities. It had links to many other programmes such as the Joint Global Ocean Flux Study (JGOFS) (Wallace, 2001) and the Tropical Ocean and Global Atmosphere (TOGA) Observing System (Godfrey et al., 2001). The WOCE field programme took approximately ten years to complete, but most observations were carried between 1990 and 1998. The synthesis and modelling components of WOCE and the wider scientific exploitation of WOCE results will continue for many years.

The main aim of WOCE observations was to acquire a high quality data set, which in some sense represented the "state of the oceans" during the 1990s. These data are being, and will continue to be, used to improve models of the ocean-atmosphere coupled system with the aim of improving our ability to forecast changes in ocean climate. They also provide a 1990s baseline against which to measure future (and past) changes.

The WOCE Hydrographic Programme

Three types of hydrographic survey were used: The first, known as the One-time Survey, involved sampling coast-to-coast across all the main ocean basins. Each observation site or "station" measured properties from the surface to within a few meters of the sea floor. Stations were typically 30 nm, (~55 km) apart, with the station spacing chosen to help document the oceanic meso-scale variability with its typical scale of 100-200 km. Closer station spacing was used over steep seabed topography, on meridional sections through the tropics where narrow zonal currents were important and when crossing major current systems (see King, Firing and Joyce, 2001). The global network of One-time stations is shown in Figure 1. While the scientific justification of individual lines was to improve our knowledge of specific features of the ocean circulation (e.g. flow through gaps or "choke points"), the main aim of the One-time survey was to obtain a fairly uniform grid of stations in each ocean basin (WCRP, 1988a,b). This was particularly the case in the North and South Atlantic, where the TTO (Brewer et al, 1983) and SAVE programmes, respectively, had sampled extensively during the 1980s and thus provided valuable insight into the large-scale oceanography of these basins.

The second part of the hydrographic survey was the repeat hydrography (see Figure 2). Here, multiple transects were made along the same cruise track at various time intervals, usually sampling for a reduced suite of parameters. Frequently these included only temperature, salinity, and dissolved oxygen. Some of the repeat lines coincided with lines in the One-time Survey. Sampling was not always to the bottom on these cruises, which were generally made where the

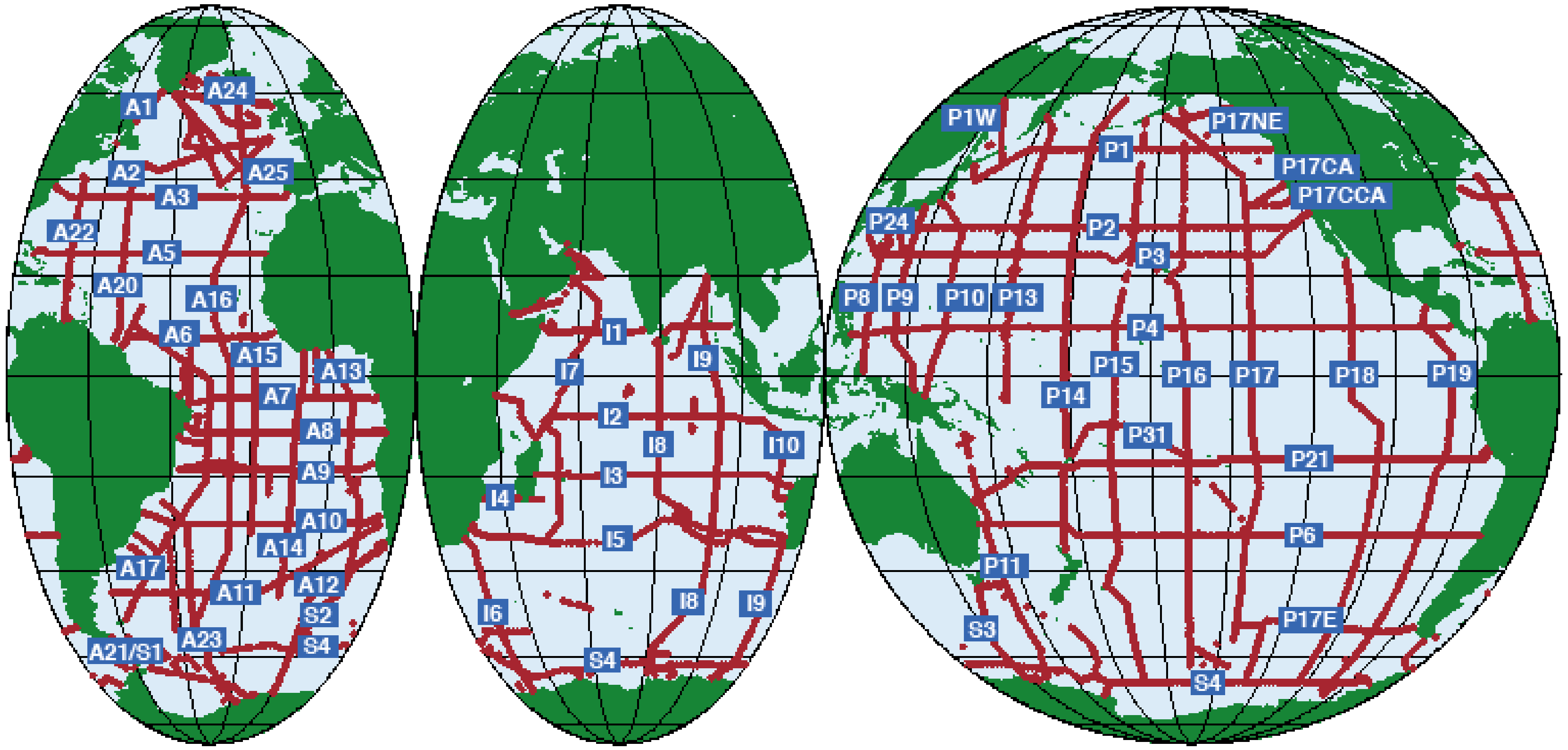

Figure 1. Stations occupied during the WOCE One-time Survey

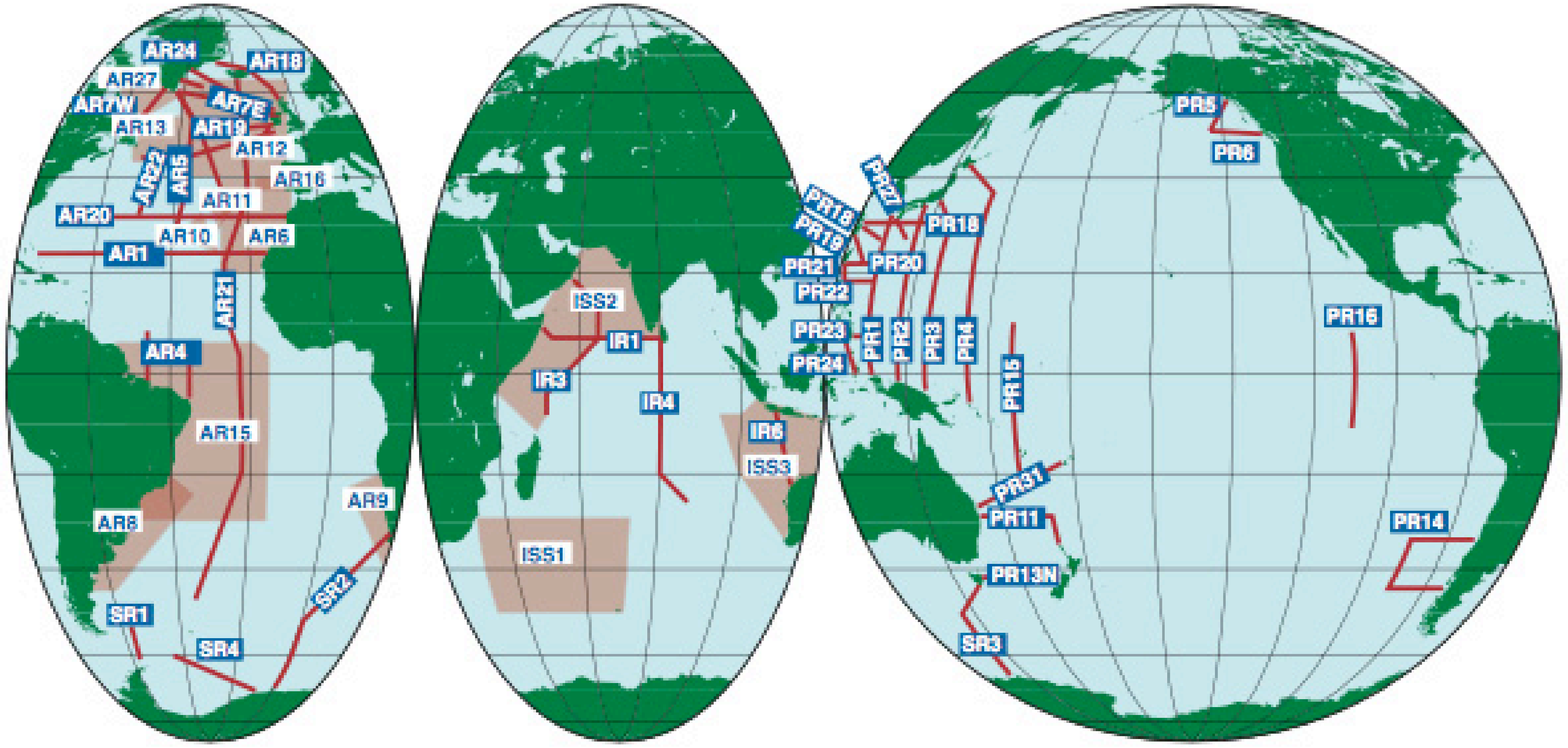

Figure 2. Schematic of WOCE Repeat Survey lines.
The shaded regions are Intensive Study Areas

variability was particularly important (e.g., across the outflows from the Nordic and Labrador Seas), and where such highly intensive surveys could be carried out practicably. Data from these cruises are included in the archived and online WHP data sets, but are only used in this volume in the horizontal maps.

The third portion of the survey was a series of individual stations that were sampled at approximately monthly intervals over periods of several years. These are generally referred to as Time Series stations. These were (and continue to be) sampled to the bottom, but the suite of samples does not include all the tracers sampled on the One-time lines. Only three such stations were occupied in the Atlantic, one in the Norwegian Sea, Ocean Weather Ship Station M, (66°N, 2°E), another near the Canary Islands as part of the European Station for Time-series in the Ocean, Canary Islands (ESTOC) at 29°10'N, 15°30'W, (http://www.estoc.es/en), and the Bermuda Atlantic Time-series Study (BATS, 31° 40'N, 64° 10'W) (http://bats.bios.edu) (Phillips & Joyce, 2007). Data from these stations are not incorporated in the atlas, except as part of the horizontal maps.

The original plan was to complete the survey of each ocean within a one to two year period. For various logistical and resource reasons this was not achieved, and the cruises within each ocean span several years (see Table 1, page xii). However, we believe that the data provide as near synoptic a view of the state of the ocean during the 1990s as was possible, and that the inconsistencies introduced by non-synoptic sampling are relatively minor. The WHP data also fill many gaps in our knowledge of the ocean, as well as providing, for the first time, comprehensive global coverage of many parameters (e.g., CFCs, helium, tritium and $\Delta^{14}C$) first measured during the GEOSECS Expeditions during the 1970s (Bainbridge, Geosecs Atlantic Expedition, Vol 2: Sections and Profiles. National Science Foundation, Washington, D.C., 1981).

The sampling techniques used during the WOCE One-time cruises have been developed and tested rigorously over many years (WHPO, 1991). Each station consisted of a surface to near-bottom lowering of a conductivity, temperature, depth (CTD) probe that also measured *in situ* pressure. Most of these were also equipped with continuous-sampling dissolved oxygen sensors. These data were transmitted up the conducting cable and logged on board the ship. Discrete samples of water were collected at depths selected throughout the water column to resolve the vertical structure. These discrete samples were used for chemical analysis and for quality control of the continuously sampled salinity (derived from temperature, conductivity and pressure) and oxygen data. Rosette samplers used in WOCE were of the type developed during the GEOSECS programme, and generally were able to take either 24 or 36 10-litre samples during each cast. This sampling scheme supplied enough water that all samples could be drawn from one rosette bottle. (On WOCE cruises before 1993, when accelerator mass spectrometry was accepted as suitable, a separate, large-volume cast was required for $\Delta^{14}C$ samples.) Note that not all parameters were sampled at all depths or all stations.

Several calibration cruises were carried out as part of the run-up to the WHP:

- CFC cruise run by Weiss (Wallace, 1991)
- S, O_2 cruise run by Joyce (Joyce et al., 1992; Culberson et al, 1991)
- CO_2 calibrations run by the Department of Energy in US (as discussed by e.g. Lamb et al., 2002)

A complete list of all WOCE One-time cruises in the Atlantic Ocean is given in Table 1. This list includes details of the dates of occupation for each section (from which the departure from synopticity can be assessed), which parameters were sampled and the investigator and institute responsible for the analysis of each. It should be noted that cruise A16 was occupied as three separate cruises during 1988-1989, prior to the start of the official WOCE period. Station spacing and sampling were sparser than on the other WOCE Atlantic cruises, but it was not considered likely that funding would be available to repeat the lines during WOCE. As it happened, the northern portion was reoccupied by the British in 1998 (Smythe-Wright, 1999). As stated above, not all cruises sampled all parameters.

WHP oversight

Throughout the programme, the international community provided oversight through a WOCE Hydrographic Programme Planning Committee. This committee, chaired at various times by Drs. Terrence Joyce (Woods Hole, USA), Jens Meincke (University of Hamburg, Germany), Peter Saunders (Institute of Oceanographic Sciences, UK), James Swift (Scripps Institution of Oceanography, USA), and Piers Chapman (Texas A&M University, USA), was charged with ensuring that data were collected and processed according to agreed specifications. A Data Analysis Centre, initially at Woods Hole (headed by T. Joyce) but later at Scripps (under J. Swift), collated all the individual data sets arising from each cruise and arranged for the quality control procedures, necessary to ensure the required high quality, to be carried out.

The WHP Special Analysis Centre (WHP-SAC) in Hamburg, Germany, served to collate the WHP data set in association with the WOCE Hydrographic Programme Office (WHPO) and to quality control the data on a cruise by cruise basis.

All WOCE data used in this atlas were obtained from the WHPO, the functions of which have passed to the CLIVAR and Carbon Hydrographic Data Office (CCHDO http://cchdo.ucsd.edu). The full WHP data sets obtained on all cruises are available on a DVD set issued by the WOCE International Project Office and the U.S. National Ocean Data Center (http://www.nodc.noaa.gov/WOCE).

Table 1. Vertical sections displayed in the Atlantic Ocean Atlas (see plate 2, page 1). A dash (-) means that samples for this parameter were not collected during the cruise in question or were not made available in time. Affiliations are at time of cruise.

WOCE Section *EXPOCODE*	**Dates**	**Ship**	**PI**	**CTD/S/O$_2$**	**Nutrients**	**CFC**	**He/Tr**	**Δ^{14}C**	**Alk./TCO$_2$**
A1 *06MT30_3*	Nov 15-Dec 19, 1994	Meteor	J. Meincke[46]	A. Sy[47], I. Horn[47], R. Kramer[47], F. Oestereich[47]	D. Kirkwood[51]	M. Rhein[52]	R. Bayer[49]	R. Bayer[49]	-
A1E *06MT18_1*	Sep 02-Sep 26, 1991	Meteor	J. Meincke[46]	J. Swift[24], A. Sy[47]	J. Swift[24]	W. Roether[48]	R. Bayer[49]	R. Bayer[49]	K. Johnson[22]
A1W *18HU95011_1*	June 08-July 04, 1995	Hudson	J. Lazier[50]	J. Lazier[50]	P. Strain[50], P. Clement[50]	P. Jones[50]	P. Schlosser[11]	-	J. Lazier[50]
A2 *06MT30_2*	Oct 12-Nov 12, 1994	Meteor	P. Koltermann[47]	P. Koltermann[47]	J. Duinker[52], L. Mintrop[52]	W. Roether[48]	R. Bayer[49]	R. Bayer[49]	-
06MT39_3	June 11-July 03, 1997	Meteor	P. Koltermann[47]	R. R. Kramer[47], A. Frohse[47]	R. Kramer[47]	K. Bulsciewicz[48]	-	-	-
A3 *90CT40_1*	Sep 11-Nov 21, 1993	Prof. Multanovskiy	V.Tereschenkov[7]	S. Dobroluybov[53], V.Tereschenkov[7], U. Reva[7] , S. Borodkin[7], E. Yakushev[7]	V. Konnov[7], E. Yakushev[7]	-	-	-	-
A5 *29HE06_1* *29HE06_2* *29HE06_3*	July 14-Aug 15, 1992	Hespérides	G. Parrilla[54]	G. Parrilla[54], H. Bryden[55], J. Escánez[54], R. Molina[54]	A. Cruzado[56]	W. Smethie[11]	-	W. Broecker[11]	F. Millero[21], A. Ríos[57]
A6 *35A3CITHER1_2*	Feb 13-Mar 19, 1993	L'Atalante	C. Colin[58]	M. Arhan[59,69], H. Mercier[59,69]	C. Oudot[58]	C. Andrie[61]	P. Jean-Baptiste[70]	-	-
A7 *35A3CITHER1_1*	Jan 02-Feb10, 1993	L'Atalante	A. Morliere[58]	M. Arhan[59,69], H. Mercier[59,69]	C. Oudot[58]	C. Andrie[61]	P. Jean-Baptiste[70]	-	-
A8 *06MT28_1*	Mar 29-May 11, 1994	Meteor	T. Müller[52]	T. Müller[52]	D.J. Hydes[63], S. Kohrs[52]	A. Putzka[48]	W. Roether[48], A. Putzka[48]	-	K. Johnson[22]
A9 *06MT15_3*	Feb 10-Mar 23, 1991	Meteor	G. Siedler[52]	D. Nehring[64], G. Siedler[52]	D. Bos[24], J. Jennings	D. Wallace[65]	P. Beining[48]	M. Arnold[49]	D. Wallace[65], K. Johnson[22]
A10 *06MT22_5*	Dec 27-Jan 31, 1993	Meteor	R. Onken[52]	T. Müller[52]	J. Jennings[18], L. Gordon[18]	W. Roether[48]	W. Roether[48], A. Putzka[48]	-	K. Johnson[22], D. Wallace[65]
A11 *74DI199_1*	Dec 22 1992 - Feb 01, 1993	Discovery	P. Saunders[63]	B. King[63], S. Bacon[55], P. Chapman[66]	D. Hydes[63]	D. Smythe-Wright[55]	-	-	-
A12 *06AQANTX_4*	May 21-Aug 05, 1992	Polarstern	P. Lemke[67]	M. Schröder[67]	G. Kattner[67]	W. Roether[48]	W. Roether[48]	-	-
A13 *35A3CITHER3_2*	Feb 18-April 02, 1995	L'Atalante	M. Arhan[69]	M. Arhan[69]	P. Morin[69]	L. Mémery[61]	W. Roether[48]	-	M. Gonzalez[68], L. Bingler[35]
A14 *35A3CITHER3_1*	Jan 13-Feb 16, 1995	L'Atalante	H. Mercier[69]	H. Mercier[69]	X. Salagado[57]	L. Mémery[61]	W. Roether[48]	-	A. Ríos[57], L. Bingler[35]
A15 *316N142_3*	Apr 03-May 21, 1994	Knorr	W. Smethie[11]	J. Swift[24]	J. Swift[24]	W. Smethie[11]	W. Jenkins[33]	-	C. Goyet[33]

WOCE Section *EXPOCODE*	Dates	Ship	PI	CTD/S/O_2	Nutrients	CFC	He/Tr	$\Delta^{14}C$	Alk./TCO_2
A16N *32OC202_1*	July 23-Sep 01, 1988	Oceanus	M. McCartney[11]	M. McCartney[33]	J. Jennings[18]	J. Bullister[33]	-	-	-
A16S *318MSAVE5*	Jan 23-Mar 08, 1989	Melville	W. Smethie[11], M. McCartney[11]	R. Williams[24]	L. Gordon[18]	R. Weiss[24]	W. Smethie[11]	R. Key[20]	-
A16C *318MHYDROS4*	Mar 13-Apr 19, 1989	Melville	L. Talley[24] , M. Tsuchia[24], J. Orr[20]	J. Swift[24]	J. Swift[24]	R. Weiss[24], W. Smethie[11]	W. Jenkins[33]	R. Key[20]	-
A17 *3230CITHER2_1*	Jan 04-Mar 21, 1994	Maurice Ewing	L. Mémery[61]	L. Mémery[61], M.Arhan[69], H. Mercier[69]	A. Ríos[57]	L. Mémery[61]	P. Jean-Baptiste[70]	-	L. Bingler[27], L. Arlen[69] A. Ríos[57]
A20 *316N151_3*	July 17-Aug 10, 1997	Knorr	R. Pickart[33]	R. Pickart[61]	J. Jennings[18], B. Sullivan[18]	W. Smethie[11]	S. Birdwhistell[33]	C. Sabine[20]	C. Sabine[20], R. Wilke[22]
A21 *06MT11_5*	Jan 23-Mar 08, 1990	Meteor	W. Roether[48]	G. Rohardt[67], E. Fahrbach[67]	J. Swift[24], F. Delahoyde[24]	W. Roether[48]	W. Roether[48]	P. Schlosser[49], K. Munnich[49]	D. Chipman[11], T. Takahashi[11]
A22 *316N151_4*	Aug 15-Sep 03, 1997	Knorr	T. Joyce[33]	T. Joyce[33]	L. Gordon[18]	W. Smethie[11]	W. Jenkins[33]	R. Key[20]	-
A23 *74JC10_1*	Mar 20-May 06, 1995	James Clark Ross	K. Heywood[71], B. King[63]	K. Heywood[71], B. King[63]	R. Sanders[71]	A. Watson[19]	C. Rüth[48]	-	J. Robertson[72]
A24 *316N151_2*	May 30-July 05, 1997	Knorr	L. Talley[24]	L. Talley[24]	L. Talley[24]	R. Weiss[24]	P. Schlosser[11]	-	F. Millero[21], D. Wallace[22]
A25 *74DI230_1*	Aug 07-Sep 17, 1997	Discovery	S. Bacon[55]	S. Holley[55], S. Cunningham[55]	S. Holley[55]	D. Smythe-Wright[55]	-	-	M. Rodriguez[57]

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The atlas DVD includes this final data set, as well as a number of chemical parameters not available in the printed atlas and many additional standard depth and neutral density surface maps.

ATLAS FORMATS

The plates in this atlas are presented in the following order: Bathymetry and station positions, vertical sections, property-property plots and basemaps, and finally the horizontal maps.

Vertical sections

The hydrographic and chemical properties measured along each line are shown in the vertical sections in this atlas, plotted as a function of depth. For each line, sections are given for up to fifteen parameters: Potential temperature, salinity, neutral density, potential density, oxygen, nitrate, phosphate, silicate, CFC-11, total CO_2, alkalinity, helium, δ^3He, tritium and Δ^{14}C. CFC-12 tends to duplicate the structures shown in the CFC-11 plots.

Sections of potential temperature, salinity, neutral density and potential density are constructed from CTD data, not discrete bottle samples. Neutral density was calculated from the raw data following the method of Jackett and McDougall (1997), and potential density using the 1980 Equation of State (UNESCO, 1981). Potential density sections of σ_0 are shown above 1000 m, of σ_2 from 1000-3000 m and of σ_4 below 3000 m.

The sampling strategy for WOCE cruises generally provided closer station spacing over ocean ridges and continental slope regimes, where the expected scales of variability are smaller than in the oceanic regime. Vertical sections were constructed using optimal mapping (Gandin, 1965; Bretherton et al., 1976; Roemmich, 1983). This algorithm simply solves an equivalent least square problem applied to a practical subset of nearby measurements, i.e. a minimum variance solution. The horizontal grid for the mapping placed three additional equally-spaced profiles between each pair of stations. A uniform vertical grid spacing of 10 m was adopted for mapping the CTD data, whereas bottle data were mapped onto a vertical grid whose spacing increases progressively from 10 m near the sea surface to a maximum of 100 m at depths greater than 1000 m. Elliptical correlation areas were allowed to vary within the grid as a function of the local grid spacing. At each grid point a horizontal: vertical correlation length ratio of 7:2 (7:4) times the local grid spacing was used while mapping CTD (bottle) data. All gridded property fields were initially machine-contoured, but the resulting patterns were manually edited after careful inspection of property values measured at each sample position.

The vertical sections are constructed as a function of cumulative distance along the line, starting at the westernmost or southernmost station. Each section consists of an upper panel showing the sea surface to 1000 m and a lower panel showing the full depth range. For the sections a vertical exaggeration distortion (distance: depth) of 1000:1 is used in the full water-column plots and of 2500:1 in the expanded plots of the upper 1000 m. Station locations are indicated with tick-marks at the top of the upper panel. Interpolated latitude/longitude along the section is shown with tick-marks at the top of the lower panel. The bottom depth at station locations is taken from ship records, and the altimeter-derived bathymetric data (Smith and Sandwell, 1997) was projected between stations to construct the bottom topography used in the sections.

Contour intervals have been selected to emphasize the important features within each set of measurements Colours have been chosen as far as possible to agree with those used in the GEOSECS atlases, with the exceptions of the CFCs, tritium, δ^3He, and Δ^{14}C. The colour scheme chosen is shown in Figure 3.

Either three or four shades of each colour have been used for all properties, varying from 100% of the base colour at one extreme of the property to 25% at an intermediate level. Isolines where colour or shade changes occur have been selected to illustrate the major water masses of the Atlantic Ocean, and do not therefore necessarily correspond to the same isoline in the other volumes of the WOCE atlases. Also for this reason, not all colours appear in all sections within the Atlantic atlas. While efforts were made to keep the contour interval constant within a particular colour shade, this was not always possible. Neighbouring contours are clearly marked where this occurs. Contour intervals may also change from one shade to another. Grey shading is used to indicate regions where no data were collected, generally below the maximum depth of the stations, and at the ends if a particular parameter was not sampled over the full section. Grey shading is also used subjectively within the figures if there are large regions of no sampling, where the objective interpolation errors were especially large.

Property-property plots

Scatter plots of two different variables are frequently used to discriminate between different water masses. There are many different combinations of property-property plots available for the different parameters shown in the atlas. The printed atlas shows the parameters only against potential temperature.

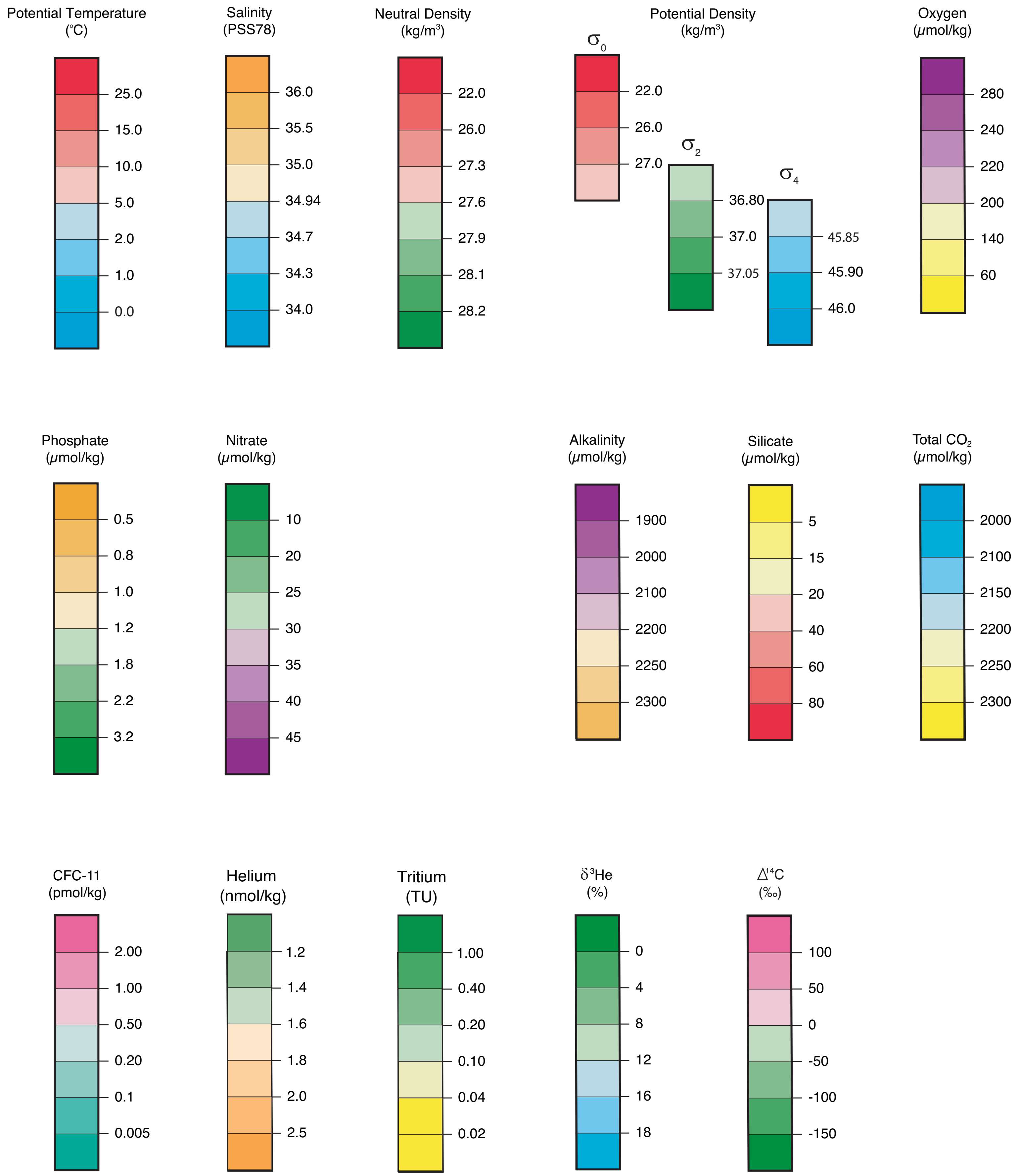

Figure 3. Vertical section and property-property plot colour scheme

These are among the more commonly used relationships, but researchers can obtain additional property-property plots from the electronic version of the atlas. The plots include data from all stations along a given line, separated by colour. The colour separation for the property-property plots in the Atlantic atlas is a function of distance along the section as shown in the individual indicator maps.

Horizontal maps

To demonstrate the distribution of water masses within the Atlantic Ocean, maps of potential temperature, salinity, neutral density, neutral surface depth, oxygen, phosphate, nitrate, and silicate are shown at a number of horizons, both neutral surfaces (Jackett and McDougall, 1997) and depth levels. The depth levels above 200 m with stronger seasonal variability are not included due to inadequate sampling. Because the important water masses differ from one ocean to another, the choice of layers is not consistent between the atlas volumes for the four oceans. Depth levels shown in the printed version of the Atlantic atlas are 200, 500, 1000, 1500, 2500, 3500 meters and the bottom. The isopycnal levels shown in the Atlantic printed atlas are 26.20, 27.22, 27.95, 28.05, and 28.10 kg/m^3, to portray such specific water masses as Labrador Sea Water, Mediterranean Sea Water, and Antarctic Bottom water. Colour breaks on horizontal maps are chosen to show clearly the distribution of waters along the different levels. Colour ranges are given in the individual plates. Similar to the Pacific WOCE atlas Mollweide geographic projection is used.

In a deviation from the other WOCE atlases the maps of the Atlantic WOCE Atlas are based on the WOCE Global Hydrographic Climatology (Gouretski and Koltermann, 2004), representing gridded distributions of temperature, salinity, oxygen, phosphate, nitrate, and silicate for 45 depth levels between the surface and 6000 meters with the resolution along latitude and longitude of 0.5 degrees. The WOCE Global Hydrographic Climatology WGHC is also available on the DVD version of this Atlas.

Since the WOCE hydrographic dataset alone does not allow a sufficient spatial resolution between the section lines, this dataset was expanded through the addition of the non-WOCE hydrographic data taken from the World Ocean Database 1998 (Levitus et al., 1998), so that the global composite dataset includes 1,059,535 hydrographic profiles. For bathymetry information needed to produce the bottom relief map and to provide the bottom mask for the property maps at levels and neutral surfaces the global 5-arcmin gridded topography data ETOPO-5 was used (National Geophysical Data Center, 1988).

To identify erroneous observations in the composite dataset a quality check procedure was implemented which consisted of several steps. After deleting crude outliers random errors were identified by checking the data in the density-parameter space. The method is based on the experimental fact that relations between the water density and other parameters are well defined locally and are relatively tight below the thermocline level. Guided by the random error statistics the composite dataset was further subdivided into two datasets: 1) a reference data set of 19,867 profiles from high quality cruises occupied after 1970 and 2) a historical data set of 1,039,668 profiles from cruises before 1970.

During the second step of the quality control inter-cruise property offsets (systematic errors) were calculated for the reference subset of the data, using the method successfully applied to an earlier version of the data set (Gouretski and Jancke, 2001). For a geographical set of intersecting cruise lines this method estimates systematic errors for each cruise based on the inter-cruise property offsets within the respective cross-over areas. The optimal corrections are then applied to the reference dataset, which in turn is used to estimate systematic errors specific for each cruise of the historical dataset.

To compute climatological property distributions an optimal interpolation method (Gandin 1965; Bretherton et al., 1976) was used, which requires knowledge of the estimated property field, the spatial correlation for the field of increments (observation minus estimated field), and the signal-to-noise ratio. A negative squared exponential has been favoured as the shape of the spatial correlation function with the e-folding scale of 450 km in the open ocean areas. A reduced value of the decorrelation scale was used in the coastal areas to allow a better spatial resolution there. The optimum interpolation was performed on surfaces of neutral density in order to avoid the production of artificial water masses which occurs when the data are interpolated on isobaric surfaces (Lozier et al., 1994). The interpolation algorithm guarantees the vertical stability of each gridded vertical profile.

Property distributions are shown as standard contour lines overlaid on a colour background. Each of the four shades of two colours used in the maps occupy about the same geographical area. A digital ETOPO-5 ocean bottom bathymetry compiled by the NOAA National Geophysical Data Center was used to create bottom masks for the maps.

Data quality control

The WHP data were submitted by a large number of principal investigators (see Table 1), who each invested a large amount of time in collecting, analysing, calibrating, proofing, and formatting the data. The data sets were then submitted to the WOCE Hydrographic Programme Office, where they were further formatted, merged, and placed online. Some of the data sets received extensive quality control, while others did not. When obtained for the atlas-making process, each data set still contained errors or low quality data that had not been flagged as such. Data quality errors were primarily evident as outliers in any of the three plotting procedures: vertical sections, property plots, and maps. Each of these revealed different types of errors. Through extensive communication with the WHPO and with the individual investigators, the errors were tracked, a decision or correction was made, and the WHPO data files were edited. The complete data set at the time of publication of this atlas is similar to that which was distributed in 2002 on DVD (http://www.nodc.noaa.gov/WOCE), but contains corrections. The WHPO continues to update data sets, and so the basic data are best obtained through the WHPO's website (http://cchdo.ucsd.edu).

APPENDIX - Parameter definitions

Standard definitions for the parameters shown in this atlas are as follows. Further details can be obtained from the suggested references or from a standard textbook such as Pond and Pickard (1995):

Potential temperature (°C)

The potential temperature, θ, is defined as the temperature that a sample of seawater would attain if brought adiabatically (without gain or loss of heat to the surroundings) from the pressure appropriate to its depth to the ocean surface (see e.g., Feistel, 1993).

Salinity (PSS78 scale)

The salinity, S, is essentially a measure of the mass of dissolved salts in one kilogram of seawater. Because the major ions in seawater are found in a constant ratio to each other, the salinity of a sample of seawater is now measured in terms of a conductivity ratio relative to a standard solution of potassium chloride. Thus salinity values according to the current definition of the Practical Salinity Scale of 1978 (PSS78) are dimensionless with no units. (See e.g., UNESCO, 1981).

Neutral density (kg/m^3)

Neutral density, γ^n, gives a very close approximation to truly neutrally buoyant surfaces over most of the global ocean. γ^n is a function of salinity, *in situ* temperature, pressure, longitude, and latitude. (See e.g., Jackett and McDougall, 1997). By convention all densities are quoted as the actual density minus 1000 kg/m3.

Potential density (kg/m^3)

The potential density, σ, is the density a parcel of water would have if it were moved adiabatically to a standard depth without change in salinity. σ_0, σ_2 and σ_4 are the potential densities of a parcel of seawater brought adiabatically to pressures of 0, 2000 and 4000 decibars, respectively. (See e.g., Pond and Pickard, 1995).

Oxygen (µmol/kg)

The dissolved oxygen content, O_2, can be used to trace certain water masses. Oxygen enters the ocean from the atmosphere, but is also produced in the surface layers by phytoplankton and is consumed during the decomposition of organic material. This leads to relatively large changes in concentration depending on depth, position and initial solubility (which is a function of temperature and salinity). (See e.g., Broecker and Peng, 1982).

Nitrate, Nitrite, Phosphate and Silicate (µmol/kg)

Nitrate, NO_3, Nitrite, NO_2, Phosphate, PO_4, and Silicate, Si, are some of the main nutrients utilised by phytoplankton. They are also non-conservative tracers, but vary inversely with oxygen concentration in the upper- and mid-ocean. They are supplied mainly by river runoff and from sediments. (See e.g., Broecker and Peng, 1982).

Chlorofluorocarbons (pmol/kg)

Chlorofluorocarbons, CFCs, are anthropogenically produced chemicals that enter the ocean from the atmosphere. Since they have a time-varying atmospheric history, they can be used to deduce information on mixing rates in the ocean and to follow the movement of water masses forming at the sea surface (see e.g., Weiss et al., 1985).

Total Carbon dioxide (µmol/kg)

The total dissolved inorganic carbon content of seawater is defined as:

$$TCO_2 = [CO_2^*] + [HCO_3^-] + [CO_3^{2-}]$$

where square brackets represent total concentrations of these constituents in solution (in *µ*mol/kg) and $[CO_2^*]$ represents the total concentration of all un-ionised carbon dioxide, whether present as H_2CO_3 or as CO_2. (See e.g., DOE, 1994 for further details.)

Alkalinity (µmol/kg)

The total alkalinity of a sample of seawater is defined as the number of moles of hydrogen ion equivalent to the excess of proton acceptors (bases formed from weak acids with a dissociation constant $K \leq 10^{-4.5}$ at 25 °C and zero ionic strength) over proton donors (acids with $K > 10^{-4.5}$) in one kilogram of sample. Many ions contribute to the total alkalinity in seawater, the main ones being HCO_3^-, CO_3^{2-}, $B(OH)_4^-$ and OH^-. (See e.g., DOE, 1994 for further details.)

Delta Helium-3 (%)

Radioactive tracers such as delta Helium-3, δ^3He, can be used to derive quantities such as mean residence times and the apparent ages of certain water masses. Helium isotope variations in seawater are generally expressed as $\delta^3He(\%)$, which is the percentage deviation of the $^3He/^4He$ in the sample from the ratio in air (Clarke et al, 1969). This can be written as:

$$\delta^3He(\%) = 100x \left\{ \frac{(^3He/^4He)\text{sample}}{(^3He/^4He)\text{air}} - 1 \right\}$$

Tritium (TU)

Tritium (^3H) is produced naturally from cosmic ray interactions with nitrogen and oxygen and as a result of nuclear testing. It is used particularly for examining the structure of and mixing within the oceanic thermocline. If combined with Helium-3 measurements tritium can be used to calculate an apparent age of a water mass. Tritium is reported in Tritium Units, TU, which is the isotopic ratio of $^3H/^1H$ multiplied by 10^{18}. It is determined mass spectrometrically by the ^3H regrowth technique (Clarke et al, 1976) using atmospheric helium as a primary standard. (See e.g., Schlosser, 1992).

Carbon-14 (‰)

Carbon-14, $\Delta^{14}C$, ratios can be used to infer the rates of mixing in the ocean. These ratios are expressed as the per mil difference from the $^{14}C/C$ ratio in the atmosphere prior to the onset of the industrial revolution and normalized to a constant $^{14}C/^{12}C$ ratio (see e.g., Broecker and Peng, 1982). The equation used is as follows:

$$\Delta^{14}C = \delta^{14}C - 2(\delta^{13}C + 25)(1 + \delta^{14}C/1000)$$

where

$$\delta^{14}C = \frac{(^{14}C/C)\text{sample} - (^{14}C/C)\text{standard}}{(^{14}C/C)\text{standard}}$$

Carbon-13 (‰)

Carbon-13, $\delta^{13}C$, is used in a similar manner to $\Delta^{14}C$ and is defined as follows:

$$\delta^{13}C = \frac{(^{13}C/C)\text{sample} - (^{13}C/C)\text{standard} \;\; x\ 1000}{(^{13}C/C)\text{standard}}$$

Where the standard is the isotope ratio for carbon from Cretaceous belemnite used by Harold Urey in his early work (Urey, 1947).

ACKNOWLEDGEMENTS

Compilation of these atlases would not have been possible without the hard work of many individuals. Firstly, there are those who made up the scientific complement of the cruises, who collected the continuous CTD profile data together with individual water samples and who analysed them both at sea and on shore.

Secondly, there are those who worked at or with the WOCE Hydrographic Programme Offices, both Woods Hole Oceanographic Institution (under the direction of Dr. Terrence Joyce) and later at Scripps Institution of Oceanography (under the direction of Dr. James Swift). They obtained the data from the originating principal investigators, ensured that they were in a common format and then examined the final data to ensure that the high standards established for the programme were maintained throughout the many cruises. The process of compiling these atlases provided an additional level of quality control and incentive for timely acquisition and merging of the data. The WHP Special Analysis Centre (WHP-SAC) in Hamburg, Germany, served to collate the WHP data set in association with the Hydrographic Programme Office.

Thirdly, an informal WOCE Atlas Committee consisting of members of the WOCE International Project Office (WOCE IPO), the WOCE Scientific Steering Group, the WOCE Data Products Committee and the atlas Principal Investigators was set up to provide guidance and support.

There were many funding agencies from participating countries that provided the resources to allow the sampling and analysis to take place and in several cases funded the refitting of research vessels to enable them to have the increased endurance and larger scientific parties that the WHP demanded. Finally, we should recognise the contribution made by the officers and crews of research ships. Those responsible for collecting and quality controlling the individual samples from each line are listed in Table 1. The WOCE Science Steering Group and the WOCE Atlas Committee are extremely grateful to all these individuals and agencies for their support.

Compilation of this Atlantic Ocean atlas was funded by the German Bundesministerium für Forschung und Technologie and supported by the Bundesamt für Schifffahrt und Hydrographie, Hamburg, Germany. Sabrina Görcke and others at Rothenburg & Partner, Hamburg, are gratefully acknowledged for their engagement and efforts in hand-editing the final section plots. We are grateful to Jacqueline Sommerfeld from Alfred-Wegener-Institut for hand-editing and reformatting of all atlas maps. Continuing support is also appreciated throughout the long-time of putting this atlas together from Alfred-Wegener-Institut, the KlimaCampus of the Universität Hamburg. Printing was funded by grant No.11.G34.31.007 NRAL of the Government of the Russian Federation to the Faculty of Geography, Moscow State University.

Finally we are grateful to the WCRP and its sponsors, the World Meteorological Organization (WMO), the International Council for Science (ICSU) and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO).

Publication was generously supported by BP.

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