Hydrographic Atlas of the World Ocean Circulation Experiment (WOCE)

Volume 2: Pacific Ocean

Lynne D. Talley

Series edited by Michael Sparrow, Piers Chapman and John Gould

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

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	θ (°C)	S (PSS78)	γ^n (kg/m^3)	$\sigma_{0,2,4}$ (kg/m^3)	O_2 (μmol/kg)	NO_3 (μmol/kg)	PO_4 (μmol/kg)	Si (μmol/kg)	CFC-11 (pmol/kg)	TCO_2 (μmol/kg)	Alk. (μmol/kg)	δ^3He (%)	Tr (TU)	$\Delta^{14}C$ (‰)	$\delta^{13}C$ (‰)	PvP plot & Basemap
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	γ^n (kg/m^3)	θ (°C)	S (PSS78)	O_2 (μmol/kg)	NO_3 (μmol/kg)	PO_4 (μmol/kg)	Si (μmol/kg)	CFC-11 (pmol/kg)	δ^3He (%)	Tr (TU)	Δ^{14}C (‰)
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Additional depth maps are available in the electronic version of the atlas.

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	Depth (m)	θ (°C)	S (PSS78)	O_2 (μmol/kg)	NO_3 (μmol/kg)	PO_4 (μmol/kg)	Si (μmol/kg)	CFC-11 (pmol/kg)	δ^3He (%)	Tr (TU)	Δ^{14}C (‰)
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Additional neutral density maps are available in the electronic version of the atlas.

FOREWORDS

The World Ocean Circulation Experiment (WOCE) was the first project of the World Climate Research Programme and was focused on improving our understanding of the important role of the ocean circulation in climate. Its planning, observational and analysis phases, spanned two decades (1982-2002) and, by any measure, WOCE is the most ambitious, comprehensive and successful survey of the physical and chemical properties of the global ocean undertaken to date.

Throughout the 1980s, WOCE was planned to collect *in situ* data from an unprecedented multi-year seagoing campaign and from a new generation of Earth observing satellites, using them to validate and improve models of the global ocean circulation for use in climate prediction research. In the event, WOCE occupied over 23,000 hydrographic stations on 440 separate cruises between 1990 and 1998.

WOCE results are documented in almost 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. Its scientific legacy includes: significantly improved ocean observational techniques (both *in situ* and satellite-borne); 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.

WOCE opened a new era of ocean exploration. It revolutionized our ability to observe the oceans and mobilized a generation of ocean scientists to address global issues. We therefore enter the 21st century with 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 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 to WOCE within the World Climate Research Programme.

The WOCE global hydrographic survey of physical and chemical properties is one of unprecedented scope and quality and provides the baseline against which future and pre-WOCE changes in the ocean will be assessed. I am both delighted and privileged therefore to introduce the second of the four volume series of WOCE atlases describing this data set. 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.

Dr Ann Henderson-Sellers
Director of the World Climate Research Programme

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 (with some 25 countries being involved) to survey and make oceanographic measurements of the world's oceans.

Each of our lives interacts with the oceans in many different ways, but the ocean is a vast and important resource that feeds us, houses a large fraction of the planet's biodiversity, regulates our atmosphere, and plays a key role in maintaining the stability of the Earth's climate. Increasing our knowledge and understanding of the oceans is therefore of great importance. The WOCE data have established a baseline against which future changes can be compared. All predictions about global warming hinge critically on the response of the oceans. A substantial part of our uncertainty about future climate change relates to the incomplete knowledge of the oceans embedded in our climate models. The WOCE data are now a critical resource against which to test our models and to improve our predictions of climate change. As someone deeply concerned about climate change, I cannot overemphasise the importance of this. Climate change is of genuine public concern - a concern shared by BP.

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

The WOCE Atlases stand as a record of the world's oceans during the decade of the 1990s - the decade when the issue of global warming and climate change came to public attention. In years to come, this record will be increasingly used to assess the changes of climate as reflected in the oceans. This will be a measure of the effectiveness of the actions and technologies, which are being, and will be, employed to reduce greenhouse gas emissions. BP will continue to be actively involved and, by supporting the production of these atlases, hopes to achieve a much wider understanding of the current state of the oceans, as identified by WOCE, and of climate change.

Dr Tony Haywood
Group Chief Executive, BP p.l.c.

BACKGROUND

The concept of a World Ocean Circulation Experiment (WOCE) originated in the late 1970s following the first successful 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 (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 (UNESCO, 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). The hydrographic component, designed to obtain a suite of measurements throughout the global ocean, was the largest single part of the *in situ* programme.

This atlas is the second in a series of four that will present the results of the WOCE Hydrographic Programme (WHP). It focuses on the Pacific Ocean and consists of a series of vertical sections of the scalar parameters measured during a selection of the WOCE One-Time hydrographic 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 non-WOCE observations and data from the WOCE repeat hydrography programme. Finally, property-property plots of the parameters are presented for each section.

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 tide 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 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 out 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 the 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 assess future (and past) changes in the ocean.

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 metres of the sea floor. Stations were typically 30 nautical miles (≈ 55 km) apart, with the station spacing chosen to help document the oceanic mesoscale 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 WOCE Hydrographic Programme (WHP) One-Time stations is shown in Figure 1. While the scientific justification for 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 sections in each ocean basin (WCRP, 1988a, b).

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 variability was particularly important and where such highly intensive surveys could be carried out practicably.

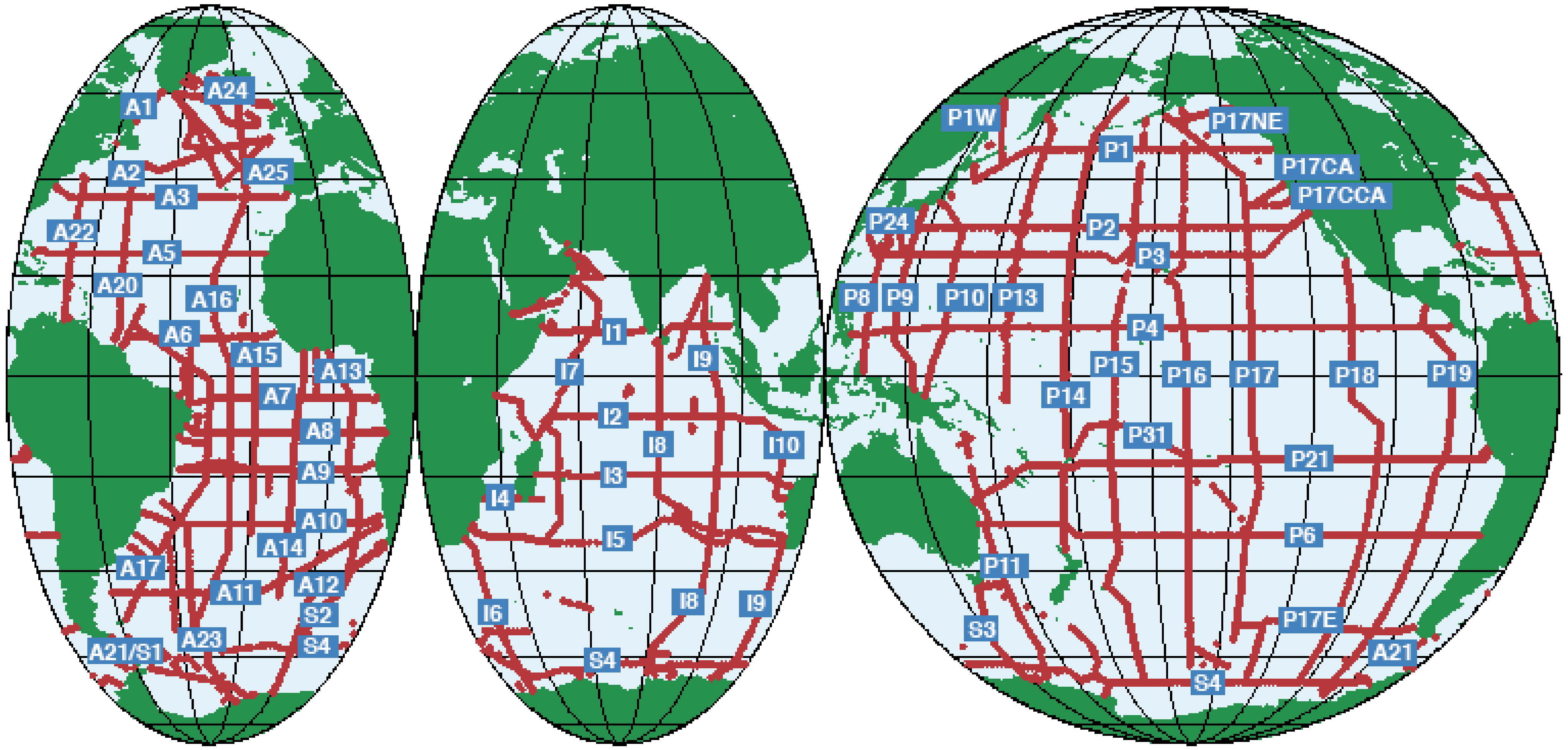

Figure 1. Stations occupied during the WOCE One-Time Survey

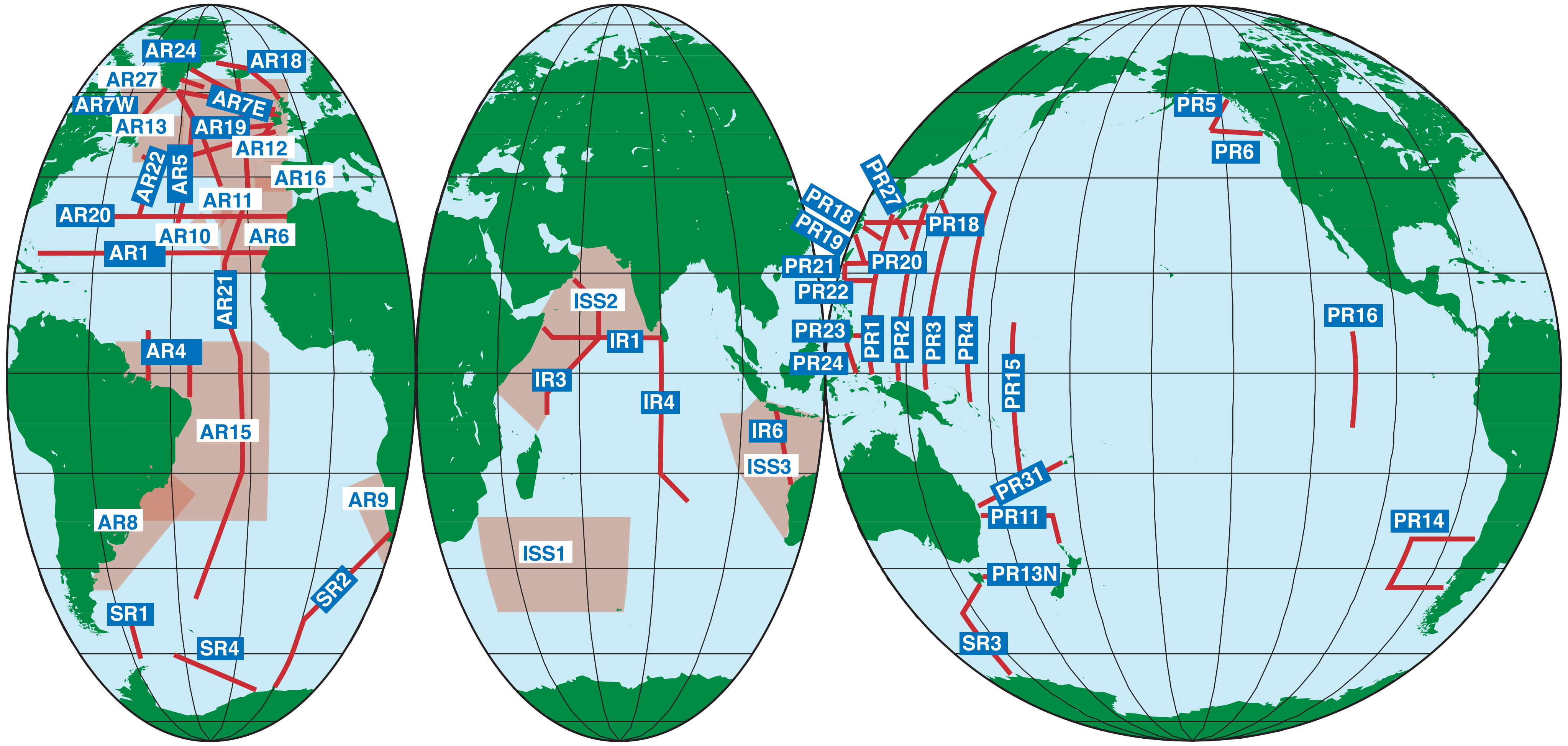

Figure 2. Schematic of WOCE Repeat Survey lines.
The shaded regions are Intensive Study Areas

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 two such stations were occupied in the Pacific, one in the subtropical North Pacific Ocean near Hawaii (Hawaii Ocean Time-series (HOT); Karl and Lukas, 1996) and the other in the Gulf of Alaska (station PAPA; Whitney and Freeland, 1999). Data from these stations are not incorporated into this atlas.

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). 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, particularly in the South Pacific, as well as providing, for the first time, comprehensive global coverage of many parameters (e.g., chlorofluorocarbons (CFCs), helium, tritium and $\Delta^{14}C$) first measured during the GEOSECS Expeditions during the 1970s (Bainbridge et al., 1981-87).

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 (O_2) 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 so that all samples could be drawn from one rosette bottle. (On WOCE cruises prior to 1993, before accelerator mass spectrometry became available as a measurement tool, a separate large-volume cast was required for the Carbon-14 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)
- Salinity, oxygen calibration cruises (Joyce et al., 1992; Culberson et al., 1991)
- Carbon dioxide (CO_2) calibrations run by the Department of Energy in the US (as discussed by e.g., Lamb et al., 2002)

A complete list of all WOCE cruises shown as vertical sections in the Pacific Ocean Atlas is given in Table 1. The cruise list includes details of the dates of occupation for each section (from which the departure from synopticity can be assessed), the parameters sampled and the investigators and institutions responsible for the analysis. It should be noted that cruises P1, P3 and P4 were carried out prior to WOCE, as were sections P16_1984A and P15 (1990 cruise), in order to fill in data gaps. Station spacing and sampling were sparser than on the other WOCE Pacific cruises, but it was not considered likely that funding would be available to repeat the lines during WOCE.

WHP oversight

Throughout the programme, the international community provided oversight through the 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) and 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. The WHP Special Analysis Centre (WHP-SAC) in Hamburg, Germany, helped to collate the WHP data set in association with the WOCE Hydrographic Programme Office (WHPO).

All WOCE data used in this atlas were obtained from the WHPO. The full WHP data sets obtained on all cruises are available on a DVD set issued by the WOCE International Project Office (http://www.woce.org) and the U.S. National Ocean Data Center (http://www.nodc.noaa.gov/woce_v3/). 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.

Table 1. Vertical sections displayed in the Pacific Ocean Atlas (see page 1). A dash (-) means that samples for this parameter were not collected during the cruise in question, were not analysed 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	$\Delta^{14}C/\delta^{13}C$	Alk./TCO_2
P1									
31TTTPS47	Aug 04-Sep 07,1985	Thomas G. Thompson	L. Talley[29]	L. Talley[29]	L. Talley[29]	R. Weiss[29]	J. Lupton[30], G. Ostlund[33]	-	-
P1W									
90BM9316_1	Aug 30-Sep 21,1993	A. Nesmeyanov	F. Whitney[10], A. Bychkov[22]	H.Freeland[10]	F. Whitney[10]	C. S. Wong[10]	C. S. Wong[10], A. Bychkov[22]	C. S. Wong[10]	C. S. Wong[10]
P2									
492SSY9310_1 *492SSY9310_2*	Oct 14-Nov 27,1993	Shoyo	T. Bando[13]	H. Yoritaka[13], K. Yokouchi[7], I. Yasuda[7], M. Fukasawa[26]	C. Saito[15]	-	-	-	-
49K6KY9401_1	Jan 07-Feb 10, 1994	Kaiyo-maru	K. Okuda[25]	M. Fukasawa[26], I. Yasuda[25], H. Yoritaka[13]	H. Kasai[8], C. Saito[15]	Y. Watanabe[35]	-	-	T. Ono[9]
49EWBO9401_1	Jan 15-Feb 04,1994	Bosei-maru	M. Fukasawa[26]	H. Yoritaka[13]	C. Saito[15]	-	-	-	-
492SSY9411_1	Nov 01-Nov 14,1994	Shoyo	Y. Iwanaga[13]	H. Kinoshita[13], K. Yokouchi[7]	C. Saito[15]	-	-	-	-
P3									
31TTTPS24_1 *31TTTPS24_2*	Mar 30-June 03,1985	Thomas G. Thompson	D. Roemmich[29], J. Swift[29], M. Hall[37], H. Bryden[37]	J. Swift[29]	J. Swift[29]	R. Weiss[29]	J. Lupton[30]	-	-
P4									
32MW893_1 *32MW893_2* *32MW893_3*	Feb 06 - May 19,1989	Moana Wave	J. Toole[37], E. Brady[37], H. Bryden[37], T. Joyce[37]	G. Knapp[37], M. Stalcup[37], R. Stanley[37]	L. Gordon[20], J. Jennings[20]	R. Weiss[29]	W. Jenkins[37]	-	-
P6									
316N138_3 *316N138_4* *316N138_5*	May 02- July 30,1992	Knorr	J. Toole[37], M. McCartney[37], H. Bryden[24]	J. Toole[37]	L. Gordon[20], J. Jennings[20]	R. Weiss[29]	W. Jenkins[37]	R. Key[23]	D. Wallace[4]
P8									
49XK9605	June 17-July 02,1996	Kaiyo	N. Yoshioka[11], D. Hartoyo[2]	Y. Kashino[11], H. Yoritaka[11], M. Aoki[17]	C. Saito[15]	-	-	C. Saito[15]	-
49K6KY9606_1	June 20-July 15,1996	Kaiyo-maru	K. Mizuno[16]	K. Mizuno[16]	N. Hagiwara[26]	S. Watanabe[9]	-	-	S. Watanabe[9]
P9									
49RY9407_1 *49RY9407_2*	July 07-Aug 25,1994	Ryofu-maru	I. Kaneko[12] , S. Kawase[12]	Y. Takatsuki[12]	H. Kamiya[12]	K. Nemoto[12]	P. Schlosser[5]	K. Hirose[14]	M. Ishii[14]
P10									
3250TN026_1	Oct 05-Nov 10,1993	Thomas G. Thompson	M. Hall[37], T. Joyce[37]	M. Hall[37], J. Swift[29]	L. Gordon[20]	M. Warner[36]	W. Jenkins[37]	R. Key[23]	C. Sabine[23]
P11									
09AR9391_2	Apr 04-May 09,1993	Aurora Australis	S. Rintoul[6]	S. Rintoul[6]	S. Rintoul[6]	-	-	-	B. Tilbrook[6]
09FA693	June 24-July 17,1993	Franklin	J. Church[6]	S. Rintoul[6], J.Church[6]	S. Rintoul[6], J.Church[6]	-	-	B. Tilbrook[6]	-
P13									
3220CGC92_1 *3220CGC92_2*	Aug 04-Oct 21,1992	John V. Vickers	J. Bullister[19], B. Taft[19]	B. Taft[19], J. Bullister[19]	K. Fanning[34]	J. Bullister[19]	W. Jenkins[37], J. Lupton[19]	P. Quay[36]	A. Dickson[29], J. Downing[3], C. Keeling[29]
P14									
316N138_7	Sep 01-Sep 15,1992	Knorr	D. Roemmich[29], B. Cornuelle[29]	D. Roemmich[29], B.Cornuelle[29], J. Swift[29]	D. Roemmich[29], B.Cornuelle[29], J. Swift[29]	M. Warner[36]	W. Jenkins[37]	R. Key[23]	J. Downing[3]
325023_1 *325024_1*	July 05-Sep 02,1993	Thomas G. Thompson	G. Roden[36]	G. Roden[36], J. Swift[29]	G. Roden[36]	M. Warner[36], R. Gammon[36]	Z. Top[33]	-	F. Millero[33], C. Winn[31]
31DSCG96_1 *31DSCG96_2*	Jan 05-Mar 10,1996	Discoverer	J. Bullister[19], G. Johnson[19], R. Feely[19], M. Roberts[19]	G. Johnson[19], J. Bullister[19]	C. Mordy[19], Z. Zhang[18]	J. Bullister[19]	-	P. Quay[36]	R. Feely[19], F. Millero[33], R. Byrne[34], R. Wanninkhof[18]
90KDIOFFE6_1	Feb 14-April 06,1992	Akademik Ioffe	M. Koshlyakov[21], J. Richman[20]	J. Swift[29]	J. Swift[29]	J. Bullister[19]	P. Schlosser[5]	P. Schlosser[5]	T. Takahashi[5], D. Chipman[5]
P15									
18DD9403_1 *18DD9403_2*	Sep 06-Nov 10,1994	John P. Tully	H. Freeland[10], J. Garrett[10]	F. Whitney[10], R. Perkin[10]	F. Whitney[10]	C. S. Wong[10]	-	C. S. Wong[10]	C. S. Wong[10]
31DSCG96_1 *31DSCG96_2*	Jan 05-Mar 10,1996	Discoverer	J. Bullister[19], R. Feely[19]	G. Johnson[19], J. Bullister[19]	C. Mordy[19], Z. Zhang[18]	J. Bullister[19]	B. Jenkins[37]	P. Quay[36]	R. Feely[19], F. Millero[33], R. Byrne[34], R. Wanninkhof[18]
3175CG90_1	Feb 22-April 16,1990	Malcolm Baldridge	D.Wisegarver[19], R. Feely[19]	J. Benson[19], D.Greeley[19] L. Mangum[19], K.McTaggart[19]	L. Moore[18]	J. Bullister[19], D. Wisegarver[19] F. Manzia[19], R. Van Woy[29]	M.Mathewson[37]	-	D. Greeley[19],P. Murphy[19],
P16									
31DSCGC91_1	Feb 14-April 08,1991	Discoverer	J. Bullister[19]	J. Swift[29], S. Hayes[19]	J. Swift[29]	J. Bullister[19]	W. Jenkins[37], J. Lupton[30]	R. Key[23]	R. Byrne[34], R. Feely[19]
31WTTUNES_2	July 16-Aug 25,1991	Thomas Washington	J. Swift[29]	J. Swift[29]	J. Swift[29]	R. Fine[33]	W. Jenkins[37]	R. Key[23]	T. Takahashi[5]. C. Goyet[37], C. Keeling[29]
31WTTUNES_3	Aug 31-Oct 01,1991	Thomas Washington	L. Talley[29]	L. Talley[29]	L. Gordon[20]	J. Bullister[19]	W. Jenkins[37], H. Craig[29]	R.Key[23], P. Quay[36]	C. Goyet[37], C. Keeling[29]
316N138_9	Oct 06-Nov 25,1992	Knorr	J. Reid[29]	J. Swift[29], J. Reid[29]	J. Swift[29], L. Gordon[20]	J. Bullister[19], W. Smethie[5], R. Weiss[29]	W. Jenkins[37]	R. Key[23]	C. Keeling[29] ,T. Takahashi[5]

P17									
31WTTUNES_1	May 31-July 11,1991	Thomas Washington	M. Tsuchiya[29]	L. Talley[29], J. Swift[29], M. Tsuchiya[29]	L. Talley[29], J. Swift[29], M. Tsuchiya[29]	R. Fine[33]	W. Jenkins[37], J. Lupton[30]	R. Key[23]	C. Goyet[37], T. Takahashi[5], C. Keeling[29]
31WTTUNES_2	July 16-Aug 25,1991	Thomas Washington	J. Swift[29]	J. Swift[29]	J. Swift[29]	R. Fine[33]	W. Jenkins[37]	R. Key[23]	T. Takahashi[5]. C. Goyet[37], C. Keeling[29]
325021_1	May 15-June 26,1993	Thomas G. Thompson	D. Musgrave[27]	D. Musgrave[27], J. Swift[29]	J. Swift[29], D. Musgrave[27]	R. Fine[33]	J. Lupton[19], Z. Top[33]	R.Key[23], P. Quay[36]	C. Keeling[29], C. Goyet[37]
316N138_9	Oct 06-Nov 25,1992	Knorr	J. Reid[29]	J. Swift[29], J. Reid[29]	J. Swift[29], L. Gordon[20]	J. Bullister[19], W. Smethie[5], R. Weiss[29]	W. Jenkins[37]	R. Key[23]	C. Keeling[29], T. Takahashi[5]
P17E									
316N138_10	Dec 04, 1992- Jan 22,1993	Knorr	J. Swift[29]	J. Swift[29]	J. Swift[29], L. Gordon[20]	W. Smethie[5], R. Weiss[29]	P. Schlosser[5], J. Lupton[19]	R. Key[23]	D. Chipman[5]
P17NE									
325021_1	May 15-June 26,1993	Thomas G. Thompson	D. Musgrave[27]	D. Musgrave[27], J. Swift[29]	J. Swift[29], D. Musgrave[27]	R. Fine[33]	J. Lupton[19], Z. Top[33]	R.Key[23], P. Quay[36]	C. Keeling[29], C. Goyet[37]
P18									
31DSCG94_1 *31DSCG94_2* *31DSCG94_3*	Feb 22-Apr 27,1994	Discoverer	B. Taft[19], G. Johnson[19], J. Bullister[19]	J. Bullister[19], B. Taft[19], G. Johnson[19]	K. Krogsland[36]	J. Bullister[19]	W. Jenkins[37]	P. Quay[36]	R. Feely[19], F. Millero[33]
P19									
316N138_10	Dec 04,1992- Jan 22,1993	Knorr	J. Swift[29]	J. Swift[29]	J. Swift[29], L. Gordon[20]	W. Smethie[5], R. Weiss[29]	P. Schlosser[5], J. Lupton[19]	R. Key[23]	D. Chipman[5]
316N138_12	Feb 22-Apr 13,1993	Knorr	L. Talley[29]	L. Talley[29], J. Swift[29]	L. Gordon[20], J. Swift[29]	R. Fine[33]	W. Jenkins[37], J. Lupton[19]	R. Key[23]	C. Keeling[29], T. Takahashi[5], R. Weiss[29]
P21									
318MWESTW_4 *318MWESTW_5*	Mar 27-June 25,1994	Melville	M. McCartney[37], H. Bryden[24]	J. Toole[37]	L. Gordon[20]	R. Fine[33], J. Bullister[19]	W. Jenkins[37]	-	F. Millero[33], C. Goyet[37]
P24									
49RY9511_2	Nov 15-Nov 30,1995	Ryofu-maru	M. Fujimura[12]	Y. Takatsuki[12]	H. Kamiya[12]	K. Nemoto[12]	-	M. Aoyama[14]	-
P31									
3250031_1	Jan 25-Feb 19,1994	Thomas G. Thompson	D. Roemmich[29]	D. Roemmich[29], S. Hautala[36],J. Swift[29]	D. Roemmich[29], S. Hautala[36]	M. Warner[36]	-	-	J. Downing[3]
S3									
09AR9404_1	Dec 13,1994- Feb 02,1995	Aurora Australis	S. Rintoul[6]	S. Rintoul[6]	S. Rintoul[6]	J. Bullister[19]	P. Schlosser[5]	B. Tilbrook[6]	B. Tilbrook[6]
S4									
90KDIOFFE6_1	Feb 14-April 06,1992	Akademik Ioffe	M. Koshlyakov[21], J. Richman[20]	J. Swift[29]	J. Swift[29]	J. Bullister[19]	P. Schlosser[5]	P. Schlosser[5]	T. Takahashi[5], D. Chipman[5]
09AR9404_1	Dec 13,1994- Feb 02,1995	Aurora Australis	S. Rintoul[6]	S. Rintoul[6]	S. Rintoul[6]	J. Bullister[19]	P. Schlosser[5]	B. Tilbrook[6]	B. Tilbrook[6]
A21									
06MT11_5	Jan 23-Mar 08, 1990	Meteor	W. Roether[28]	G.Rohardt[1], E. Fahrbach[1], J. Swift[29], F. Delahoyde[29]	J. Swift[29], F. Delahoyde[29]	W. Roether[28]	W. Roether[28]	P. Schlosser[32], K. Munnich[32]	D. Chipmann[5], T. Takahashi[5]
Electronic Atlas Only:									
P17CA									
325021_1	May 15-June 26,1993	Thomas G. Thompson	D. Musgrave[27]	D. Musgrave[27], J. Swift[29]	J. Swift[29], D. Musgrave[27]	R. Fine[33]	J. Lupton[19], Z. Top[33]	R.Key[23], P. Quay[36]	C. Keeling[29], C. Goyet[37]
P17CCA									
31WTTUNES_1	May 31-July 11,1991	Thomas Washington	M. Tsuchiya[29]	L. Talley[29], J. Swift[29], M. Tsuchiya[29]	L. Talley[29], J. Swift[29], M. Tsuchiya[29]	R. Fine[33]	W. Jenkins[37], J. Lupton[30]	R. Key[23]	C. Goyet[37], T. Takahashi[5], C. Keeling[29]
P16_1984a									
31WTMARAII	May 04-June 04,1984	Thomas Washington	R. deSzoeke[20]	R. deSzoeke[20],L. Talley[29]	R. deSzoeke[20],L. Talley[29]	-	Z. Top[33]	-	-
P13J									
49HH932_1	May 13-May 30, 1993	Hakuho Maru	K. Taira[35]	K. Taira[35]	-	-	-	-	-

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ATLAS FORMATS

Vertical sections

The hydrographic and chemical properties measured along each line are shown in the vertical sections, plotted as a function of depth and distance.

For each line sections are shown for up to fifteen parameters: Potential temperature, salinity, neutral density, potential density, oxygen, nitrate, phosphate, silicate, CFC-11, total CO_2, alkalinity, δ^3He, tritium, Δ^{14}C and δ^{13}C (see Appendix for definitions). Additional parameters, including nitrite and CFC-12, are given in the electronic version of the atlas (DVD included with atlas and online at http://www-pord.ucsd.edu/whp_atlas/). Nitrite sections are not included in the printed version because this nutrient is normally undetectable away from the thermocline except in regions such as the eastern tropical Pacific Ocean where higher concentrations are associated with the low oxygen zones north and south of the equator. CFC-12 tends to duplicate the structures shown in CFC-11.

Although samples were collected on all lines as detailed above, not all the data are represented in this atlas. Some of the tritium, Δ^{14}C (and hence δ^{13}C, which is run concurrently with Δ^{14}C analysis), and δ^3He samples were not analysed because of a shortage of funds. The lines thus affected were: P1W and P8S for tritium, and P1W, P2T, P12, P14S, P15N, and P15S for Δ^{14}C. Analysed helium samples were typically a subset of those collected on a given cruise, to provide coverage of features with a minimum number of samples. The U.S. National Science Foundation agreed to provide the additional funding to support the analysis of the Δ^{14}C samples from P1R (a repeat of P01), P14S, and P15N. The remaining tritium and Δ^{14}C samples will be stored until funding is available for their analysis, although at present the likelihood of this is not clear. The 1984 section along P16N, which included salinity, oxygen, nutrient, and tritium sampling, is included because of large data gaps in the P16N section caused by bad weather during the cruise. An additional section along P15S from 1990 is included because δ^3He and tritium were sampled on this leg and further funding was not obtained for the later WOCE occupation.

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 from 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. Complete sets of potential density referenced to 0, 2000 and 4000 m are included in the electronic version of the atlas.

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 (Bretherton et al., 1976) with weighting based on station separation rather than distance (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. A uniform grid spacing of 10 m in the vertical and 10 km in the horizontal was adopted for mapping all data. Manual corrections were typically necessary for contours with large depth excursions parallel to steep topography, to connect narrow features that the mapping algorithm broke into small pieces, and to associate extrema with data points if the mapping algorithm displaced them slightly from the sample. Contours were also manually labelled as computer contouring typically did not provide the best minimal labelling. The additional potential density sections included in the electronic version of the atlas were not subjected to this additional manual editing process.

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. Vertical exaggeration is 1000:1 for the full water-column plots and 2500:1 for 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 bathymetry is taken from ship records, where available. Some of these data sets are available from the U.S. National Geophysical Data Center (http://www.ngdc.noaa.gov/). Where not available, bottom depth from the global topography of Smith and Sandwell (1997) was used. All of the bathymetric data sets used for the sections, including the projections along the sections, are available from the electronic version of this atlas.

Contour intervals have been selected to emphasise 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 for the Pacific Ocean vertical sections is shown in Figure 3.

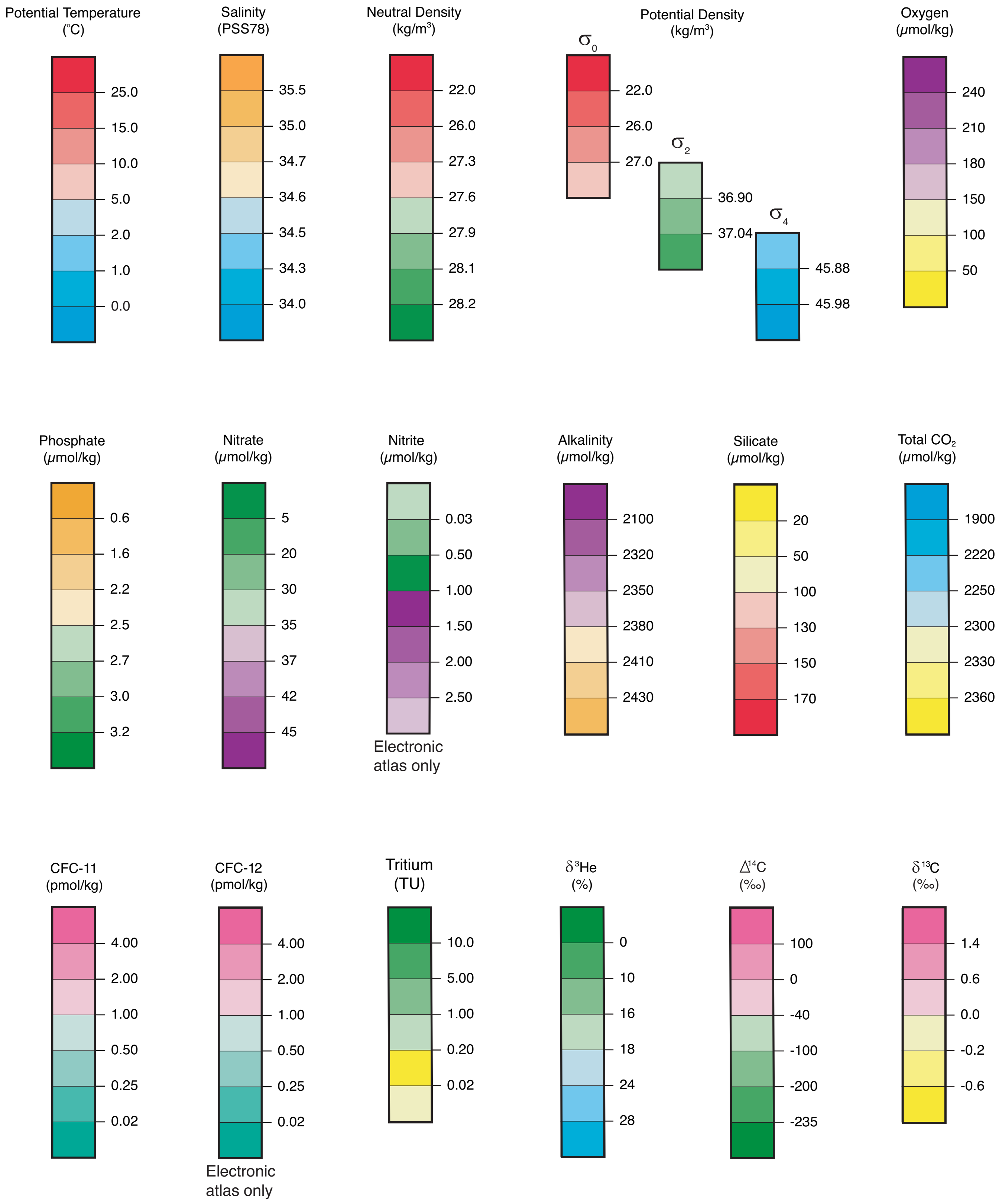

Figure 3. Vertical section colour scheme

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. Colour or shade changes illustrate the major water masses of the Pacific Ocean, and do not necessarily correspond to the same isolines in the other volumes of the WOCE atlases. Although efforts were made to keep the contour interval constant within a particular colour shade, this was not always possible. Neighbouring contours are clearly labelled where this occurs. Contour intervals may also change from one shade to another.

Property-property plots

Scatter plots of two variables are frequently used to discriminate between different water masses. There are many possible combinations of property-property plots for the parameters shown in the atlas. The printed atlas shows properties versus potential temperature, which are among the more commonly used relationships. The plots include data from all stations along a given section.

The property-property plots use up to six colours to indicate different latitude or longitude ranges, as indicated in each bathymetric station map.

Horizontal maps

To describe the spreading of water masses within the Pacific Ocean, distributions of potential temperature, salinity, neutral density, depth of the neutral density surface, oxygen, nitrate, phosphate, silicate, CFC-11, δ^3He, tritium and Δ^{14}C are shown along a small number of density surfaces and depth levels. The number of maps that can be presented in this printed atlas is necessarily fewer than required to fully describe the ocean properties, even within the major water masses. Because the important water masses differ from one ocean to another, the choice of levels is not always consistent among the atlas volumes. Depth levels shown in the printed version of the Pacific Ocean Atlas are 100 m, 500 m, 1000 m, 2500 m and 4000 m. Additional levels are available in the electronic version of the atlas.

Five neutral density surfaces were selected to portray the characteristic water masses in the Pacific Ocean. The 26.00 kg/m^3, 27.30 kg/m^3, 27.60 kg/m^3, 28.01 kg/m^3 and 28.10 kg/m^3 surfaces correspond to the upper ocean and mode waters, the Antarctic Intermediate Water, the Circumpolar and Pacific Deep Water, and the Lower Circumpolar Water and near bottom properties. Grey curves on the 26.00 kg/m^3 and 27.30 kg/m^3 maps schematically indicate the winter outcrop. Twelve additional density surfaces are available in the DVD and the online version of the atlas.

Colour breaks on horizontal maps are chosen to show clearly the spreading of waters along the different levels. Colour ranges are given in the individual plates. A Mollweide projection is used for the Pacific, Indian and Atlantic Atlases.

The horizontal maps include all WOCE data, which yield the greatest quasi-synoptic coverage and are the most reliable, but these alone are spatially too sparse to provide the distribution needed. For the Pacific Ocean maps, the quality controlled data sets of Reid (1997) have also been used for maps of potential temperature, salinity, potential density, oxygen and nutrients. The GEOSECS data sets (Bainbridge et al., 1981-87) include δ^3He and Δ^{14}C, which have also been incorporated into these maps.

The irregularly spaced station data were mapped to a uniform grid using the blockmedian and surface algorithms in the GMT mapping package (Smith and Wessel, 1990), and then contoured using the GMT grdcontour algorithm (Wessel and Smith, 1998). The resulting maps were then hand-edited based on the actual data. Editing was minimal for maps with relatively complete station coverage resulting from incorporation of extensive historical data (Reid, 1997). Editing was extensive for maps with little data other than the WHP data set because of the large separation between sections coupled with very small station separation along sections. (The GMT algorithms, which use a spline fit, as well as many objective mapping algorithms, fan the contours out in regions of sparse coverage, whereas much higher gradients, hence tighter contouring, are retained in regions of intensive coverage, such as along sections.)

The plates in this atlas are presented in the following order: (i) Bathymetry and station positions, (ii) vertical sections, property-property plots and basemaps, and finally (iii) the horizontal 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.noaa.nodc.gov/woce_v3), 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/m^3.

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 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 δ^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:

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

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:

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

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

Carbon-13 (‰)

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

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

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, 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 at 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. Those who worked at 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.

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