

Hydrographic Atlas of the World Ocean Circulation Experiment (WOCE)

Volume 4: Indian 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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TABLES OF ATLAS PLATES

Vertical Sections, Property-Property Plots and Basemaps

Zonal Sections

	θ (°C)	S (PSS78)	γ^n (kg/m ³)	$\sigma_{0,2,4}$ (kg/m ³)	O ₂ (μ mol/kg)	NO ₃ (μ mol/kg)	NO ₂ (μ mol/kg)	PO ₄ (μ mol/kg)	Si (μ mol/kg)	CFC-11 (pmol/kg)	TCO ₂ (μ mol/kg)	Alk (μ mol/kg)	$\delta^3\text{He}$ (%)	Tr (TU)	$\Delta^{14}\text{C}$ (‰)	$\delta^{13}\text{C}$ (‰)	PvP plot & Basemap
I1RS (17°N)	page 2	2	2	2	3	3	3	3	4	4	4	4	5	5	5	5	7
I1 (9°N)	8	8	9	9	10	10	11	11	12	12	13	13	14	14	15	15	17
I2 (8°S)	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	35
I3 (20°S)	36	36	37	37	38	38	39	39	40	40	41	41	42	42	43	43	45
I4 (24°S)	46	46	46	46	47	47	47	47	48	48	48	48	49	49	49	49	51
I5P (33°S)	52	53	54	55	56	57	58	59	60	61	-	-	62	63	-	-	65
I5W (33°S)	66	66	66	66	67	67	67	67	68	68	68	68	69	69	69	69	71
I5E (30°S)	72	72	72	73	73	73	74	74	74	75	75	75	76	76	76	76	77
S4I (62°S)	78	78	79	79	80	80	81	81	82	82	83	83	84	-	84	85	87

Also available in the electronic version of the atlas: Additional parameter CFC-12.

Meridional Sections

	θ (°C)	S (PSS78)	γ^n (kg/m ³)	$\sigma_{0,2,4}$ (kg/m ³)	O ₂ (μ mol/kg)	NO ₃ (μ mol/kg)	NO ₂ (μ mol/kg)	PO ₄ (μ mol/kg)	Si (μ mol/kg)	CFC-11 (pmol/kg)	TCO ₂ (μ mol/kg)	Alk (μ mol/kg)	$\delta^3\text{He}$ (%)	Tr (TU)	$\Delta^{14}\text{C}$ (‰)	$\delta^{13}\text{C}$ (‰)	PvP plot & Basemap
I6 (30°E)	page 88	88	88	89	89	89	-	90	90	90	91	91	91	92	92	92	93
I7 (60°E)	94	94	95	95	96	96	97	97	98	98	99	99	100	100	101	101	103
I7PG (62°E)	104	104	104	104	105	105	105	105	106	106	106	106	107	107	107	107	109
I8N (80°E)	110	110	110	111	111	111	112	112	112	113	113	113	114	114	114	115	117
I8I9 (95°E)	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	135
I9S (115°E)	136	136	136	137	137	137	138	138	138	139	139	139	140	140	140	141	143
I10 (110°E)	144	144	144	144	145	145	145	145	146	146	146	146	147	147	147	147	149
IR6 (1989)(116°E)	150	150	150	151	151	151	-	152	152	152	153	153	153	154	154	-	155

Also available in the electronic version of the atlas: Additional parameter CFC-12.

TABLES OF ATLAS PLATES

Horizontal Maps

Depth Maps

	γ^n (kg/m ³)	θ (°C)	S (PSS78)	O ₂ (μ mol/kg)	NO ₃ (μ mol/kg)	PO ₄ (μ mol/kg)	Si (μ mol/kg)	CFC-11 (pmol/kg)
100 m	page 156	156	157	157	158	158	159	159
500 m	160	160	161	161	162	162	163	163
1000 m	164	164	165	165	166	166	167	167
2500 m	168	168	169	169	170	170	171	171
4000 m	172	172	173	173	174	174	175	175

Additional depth maps are available in the electronic version of the atlas.

Neutral Density Surface Maps

	Depth (m)	θ (°C)	S (PSS78)	O ₂ (μ mol/kg)	NO ₃ (μ mol/kg)	PO ₄ (μ mol/kg)	Si (μ mol/kg)	CFC-11 (pmol/kg)
26.20 kg/m ³	page 176	176	177	177	178	178	179	179
26.90 kg/m ³	180	180	181	181	182	182	183	183
27.40 kg/m ³	184	184	185	185	186	186	187	187
27.80 kg/m ³	188	188	189	189	190	190	191	191
28.10 kg/m ³	192	192	193	193	194	194	195	195

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. 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 fourth volume, in the four-volume series of WOCE atlases describing the WHP data set in the Indian 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.

A handwritten signature in cursive script, appearing to read 'Ghassem R. Asrar'.

Ghassem R Asrar
Geneva, Switzerland



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.

A handwritten signature in cursive script, appearing to read 'Bob Dudley'.

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 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 (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). 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; Koltermann, Gouretski, and Jancke, 2011). This atlas, Volume 4, focuses on the Indian 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 (see Figure 1). 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.

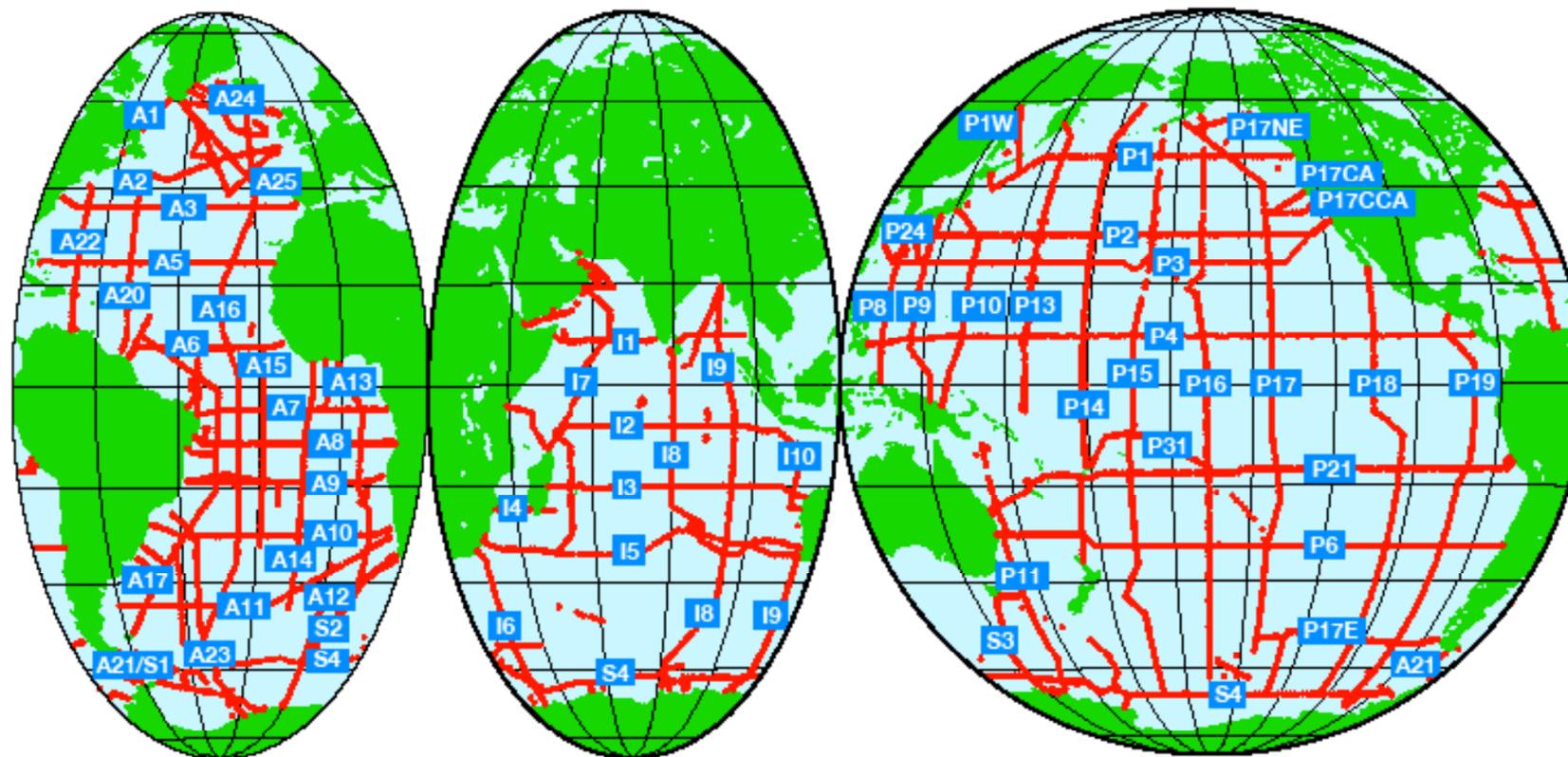


Figure 1. Stations occupied during the WOCE One-time Survey.

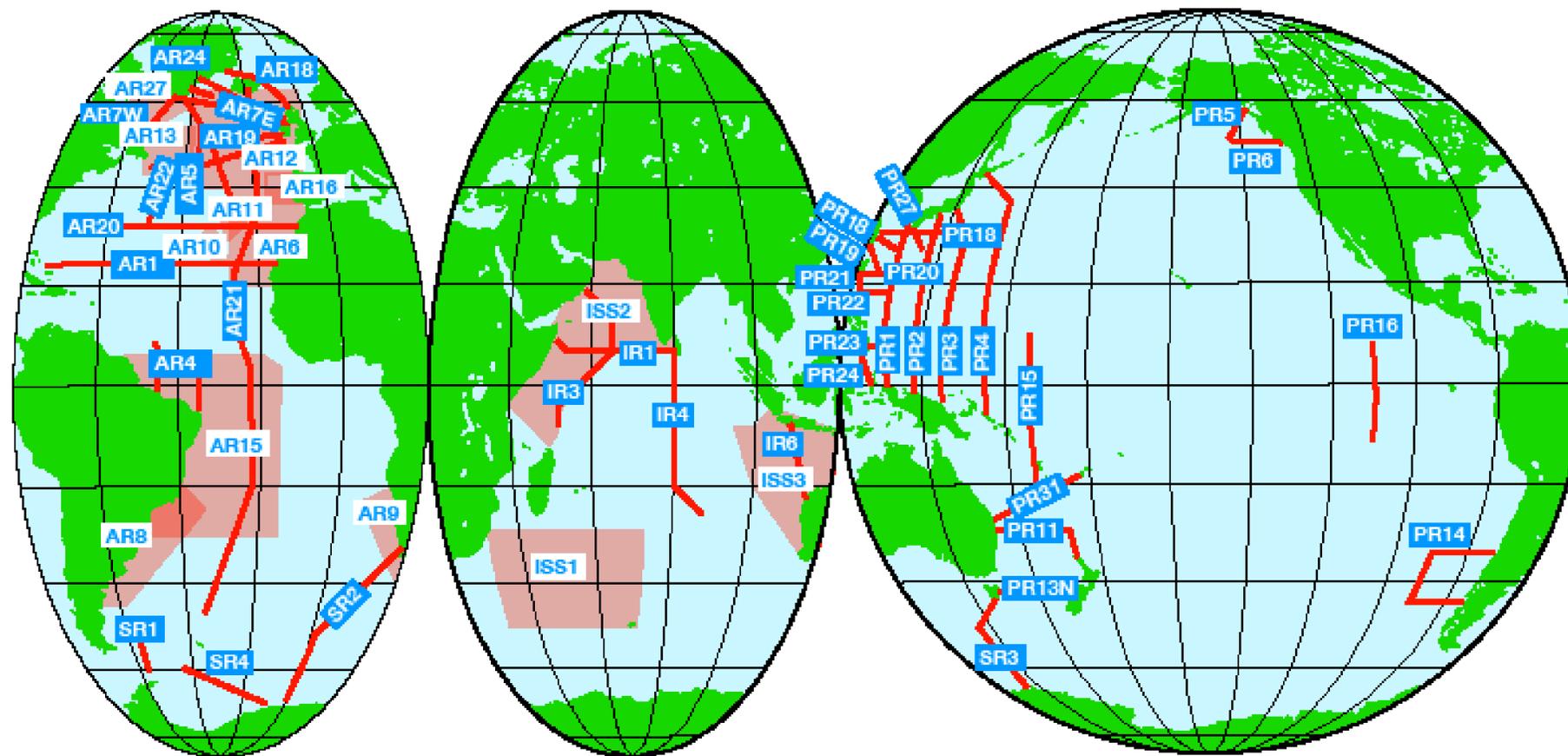


Figure 2. Schematic of WOCE Repeat Survey lines.
The shaded regions are Intensive Study Areas.

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 sampled to the bottom, but the suite of samples does not include all the tracers sampled on the One-time lines. No such time series stations were occupied in the Indian Ocean.

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. Data from the One-time survey in the Indian Ocean come closest to meeting this goal, as most lines were completed during a continuous series of surveys from late 1994 to early 1996. 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 $\Delta^{14}\text{C}$) first measured during the GEOSECS Expeditions during the 1970s (Bainbridge, et al., 1981-1987).

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 (see e.g., Lamb et al., 2002 for discussion)

A complete list of all WOCE cruises shown as vertical sections in the Indian 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 I5P and IR6 (1989) were carried out several years prior to 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 Oceanographic Institution, 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, which has now become the CLIVAR and Carbon Hydrographic Data Office (CCHDO) (<http://cchdo.ucsd.edu>). The full WHP data sets obtained on all cruises are available

Table 1. Vertical sections displayed in the Indian 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. Affiliations are at time of cruise.

WOCE Section EXPCODE	Leg	Dates	Ship	PI (Affil)	CTD/S/O ₂	Nutrients	CFC	He/Tr	$\Delta^{14}\text{C}/\delta^{13}\text{C}$	Alk/TCO ₂
I01										
316N145_11	I01W	Aug 29-Sept 28, 1995	Knorr	J.M. Morrison ⁵ , H. Bryden ⁹	J. Toole ¹⁴	L. Gordon ⁷	M. Warner ¹³	W. Jenkins ¹⁴	Z. Top ¹²	R. Key ⁸ , C. Goyet ¹⁴
316N145_12	I01E	Sept 30-Oct 16, 1995	Knorr	J.M. Morrison ⁵ , H. Bryden ⁹	J. Toole ¹⁴	L. Gordon ⁷	M. Warner ¹³	W. Jenkins ¹⁴	Z. Top ¹²	R. Key ⁸ , C. Goyet ¹⁴
I01RS										
316N145_11	I01W	Aug 29-Sept 9, 1995	Knorr	J.M. Morrison ⁵ , H. Bryden ⁹	J. Toole ¹⁴	L. Gordon ⁷	M. Warner ¹³	W. Jenkins ¹⁴	Z. Top ¹²	R. Key ⁸ , C. Goyet ¹⁴
I02										
316N145_14	I02E	Dec 2-28, 1995	Knorr	G. Johnson ⁶	G. Johnson ⁶ , B. Warren ¹⁴ , J. Toole ¹⁴	L. Gordon ⁷	J. Bullister ⁶	W. Jenkins ¹⁴ , P. Schlosser ³	R. Key ⁸	C. Winn ¹⁵ , D. Wallace ¹
316N145_15	I02W	Dec 30-Jan 22, 1996	Knorr	G. Johnson ⁶	G. Johnson ⁶ , B. Warren ¹⁴ , J. Toole ¹⁴	L. Gordon ⁷	J. Bullister ⁶	W. Jenkins ¹⁴ , P. Schlosser ³	R. Key ⁸	C. Winn ¹⁵ , D. Wallace ¹
I03										
316N145_8	I03	Apr 23-June 5, 1995	Knorr	W. Nowlin ¹⁰	J. Swift ¹¹	J. Swift ¹¹	R. Weiss ¹¹	W. Jenkins ¹⁴ , P. Schlosser ³	R. Key ⁸	F. Millero ¹² , C. Keeling ¹¹
I04										
316N145_9	I04	June 11-July 11, 1995	Knorr	J. Toole ¹⁴	J. Swift ¹¹	J. Swift ¹¹	R. Fine ¹² , W. Smethie ³	W. Jenkins ¹⁴ , P. Schlosser ³	R. Key ⁸	D. Wallace ¹
I05P										
74AB29_1	I05P	Nov 12-Dec 17, 1987	Charles Darwin	J. Toole ¹⁴ , B. Warren ¹⁴	J. Toole ¹⁴	L. Gordon ⁷	R. Fine ¹²	Z. Top ¹²	-	-
I05E										
316N145_7	I05E	Mar 10-Apr 15, 1995	Knorr	L. Talley ¹¹	L. Talley ¹¹ , J. Swift ¹¹	L. Talley ¹¹ , J. Swift ¹¹	W. Smethie ³	W. Jenkins ¹⁴ , P. Schlosser ³	R. Key ⁸	C. Keeling ¹¹ , C. Winn ¹⁵
I05W										
316N145_9	I05W	June 11-July 11, 1995	Knorr	J. Toole ¹⁴	J. Swift ¹¹	J. Swift ¹¹	R. Fine ¹² , W. Smethie ³	W. Jenkins ¹⁴	R. Key ⁸	D. Wallace ¹
I06										
35MFCIVA_1	I06S	Jan 23-Mar 9, 1993	Marion Dufresne	A. Poisson ²	M. Fieux ² , A. Poisson ²	J.F. Minster ⁴	A. Poisson ²	P. Jean-Baptiste ²	M. Arnold ² , C. Pierre ²	A. Poisson ²
35MF103_1	I06S	Feb 20-Mar 22, 1996	Marion Dufresne	A. Poisson ² , N. Metzl ² , C. Brunet ²	A. Poisson ²	A. Poisson ²	A. Poisson ²	A. Poisson ²	A. Poisson ²	A. Poisson ²
I07										
316N145_10	I07N	July 15-Aug 24, 1995	Knorr	D. Olson ¹²	J. Swift ¹¹	J. Swift ¹¹	R. Fine ¹²	Z. Top ¹²	R. Key ⁸	C. Keeling ¹¹ , C. Winn ¹⁵
I07PG										
316N145_10	I07N	July 15-Aug 24, 1995	Knorr	D. Olson ¹²	J. Swift ¹¹	J. Swift ¹¹	R. Fine ¹²	Z. Top ¹²	R. Key ⁸	C. Keeling ¹¹ , C. Winn ¹⁵
I08I09										
316N145_5	I08S	Dec 1, 1994-Jan 19, 1995	Knorr	M. McCartney ¹⁴ , T. Whitworth III ¹⁰	J. Toole ¹⁴	L. Gordon ⁷ , J. Toole ¹⁴	W. Smethie ³	P. Schlosser ³	R. Key ⁸ , P. Quay ¹³	D. Wallace ¹
316N145_6	I09N	Jan 24-Mar 6, 1995	Knorr	A. L. Gordon ³ , D. Olson ¹²	J. Swift ¹¹	J. Swift ¹¹	R. Fine ¹²	P. Schlosser ³	R. Key ⁸	-

WOCE	Leg	Dates	Ship	PI (Affil)	CTD/S/O ₂	Nutrients	CFC	He/Tr	$\Delta^{14}\text{C}/\delta^{13}\text{C}$	Alk/TCO ₂
Section EXPCODE										
I08N 316N145_7	I05E	Mar 10-Apr 16, 1995	Knorr	L. Talley ¹¹	L. Talley ¹¹ , J. Swift ¹¹	L. Talley ¹¹ , J. Swift ¹¹	W. Smethie ³	W. Jenkins ¹⁴ , P. Schlosser ³	R. Key ⁸	C. Keeling ¹¹ , C. Winn ¹⁵
I09S 316N145_5	I08S	Dec 1, 1994-Jan 19, 1995	Knorr	M. McCartney ¹⁴	J. Toole ¹⁴ T. Whitworth III ¹⁰	L. Gordon ⁷ , J. Toole ¹⁴	W. Smethie ³	P. Schlosser ³	R. Key ⁸ , P. Quay ¹³	D. Wallace ¹
I10 316N145_13	I10	Nov 11-Nov 28, 1995	Knorr	N. Bray ¹¹ , J. Sprintall ¹¹	N. Bray ¹¹ , J. Toole ¹⁴	N. Bray ¹¹ , J. Toole ¹⁴	R. Fine ¹²	W. Jenkins ¹⁴	R. Key ⁸	R. Key ⁸
IR6 (1989) 35MF62JADE_1	IR06C	July 30-Sept 9, 1989	Marion Dufresne	M. Fieux ²	M. Fieux ²	B. Coste ²	A. Poisson ²	M. Fieux ²	-	M. Fieux ²
S04I 320696_3	S04I	May 3-July 4, 1996	Nathaniel B. Palmer	T. Whitworth III ¹⁰ , J. Swift ¹¹	J. Swift ¹¹	J. Swift ¹¹	W. Smethie ³ , M. Warner ¹³	P. Schlosser ³	R. Key ⁸	F. Millero ¹² , T. Takahashi ³

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3. Columbia University, Lamont Doherty Earth Observatory (LDEO), New York, New York, USA A. L. Gordon, P. Schlosser, W. Smethie, T. Takahashi
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7. Oregon State University (OSU), Corvallis, OR, USA L. Gordon
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ATLAS FORMATS

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.

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 sixteen parameters: Potential temperature, salinity, neutral density, potential density, oxygen, nitrate, nitrite, phosphate, silicate, CFC-11, total CO₂, alkalinity, δ³He, tritium, Δ¹⁴C and δ¹³C (see Appendix for definitions). One additional parameter, CFC-12, is given in the electronic version of the atlas (DVD included with atlas and online at http://www-pord.ucsd.edu/whp_atlas). CFC-12 tends to duplicate the structures shown in CFC-11.

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 σ₀ are shown

above 1000 m, of σ₂ from 1000-3000 m and of σ₄ below 3000 m. Complete sets of potential density referenced to 0, 1000, 2000, 3000, and 4000 m are included in the electronic version of the atlas (online and DVD).

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, δ³He, and Δ¹⁴C. The colour scheme chosen for the Indian Ocean vertical sections 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. Colour or shade changes illustrate the major water masses of the Indian 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.

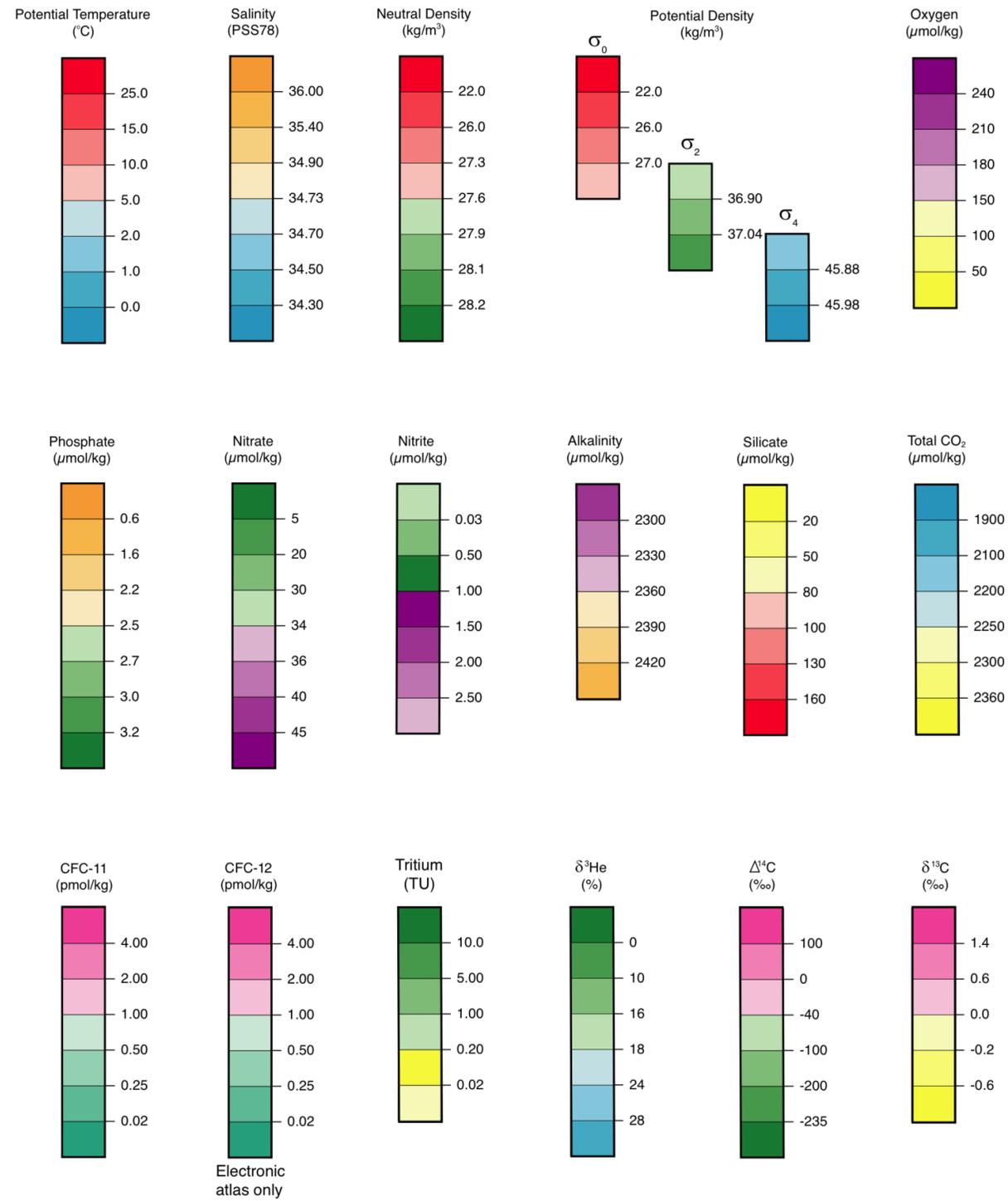


Figure 3. Vertical section colour scheme

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 Indian Ocean, distributions of potential temperature, salinity, neutral density, depth of the neutral density surface, oxygen, nitrate, phosphate, silicate, and CFC-11 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 Indian 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 Indian Ocean. The

26.20 kg/m³, 26.90 kg/m³, 27.40 kg/m³, 27.80 kg/m³ and 28.10 kg/m³ surfaces correspond to the upper ocean and mode waters, the Antarctic Intermediate Water, the Upper Circumpolar and Indian Deep Water, and the Lower Circumpolar Water. White regions in the south on the 26.20 kg/m³ and 26.90 kg/m³ maps indicate the absence of these surfaces. Grey curves on all maps schematically indicate the winter outcrop, based on very high stratification mapped on the same surfaces (not shown). 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 Indian Ocean maps, the quality controlled data sets of Reid (2003) 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 $\delta^3\text{He}$ and $\Delta^{14}\text{C}$, which have also been incorporated into the maps found on the atlas website.

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, 2003). 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, like 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.)

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 Talley et al. (2011):

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 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., Talley et al., 2011).

Oxygen ($\mu\text{mol/kg}$)

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 ($\mu\text{mol/kg}$)

Nitrate (NO_3^-), Nitrite (NO_2^-), Phosphate (PO_4^{3-}), 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 ($\mu\text{mol/kg}$)

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

$$\text{TCO}_2 = [\text{CO}_2^*] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}]$$

where square brackets represent total concentrations of these constituents in solution (in $\mu\text{mol/kg}$) and $[\text{CO}_2^*]$ 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 ($\mu\text{mol/kg}$)

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, $\delta^3\text{He}$, 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 $\delta^3\text{He}$ (%), which is the percentage deviation of the $^3\text{He}/^4\text{He}$ in the sample from the ratio in air (Clarke et al, 1969). This can be written as:

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

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 $^3\text{H}/^1\text{H}$ multiplied by 10^{18} . It is determined mass spectrometrically by the ^3He regrowth technique (Clarke et al, 1976) using atmospheric helium as a primary standard (see e.g., Schlosser, 1992).

Carbon-14 (‰)

Carbon-14, $\Delta^{14}\text{C}$, ratios can be used to infer the rates of mixing in the ocean. These ratios are expressed as the per mil difference from the $^{14}\text{C}/\text{C}$ ratio in the atmosphere prior to the onset of the industrial revolution and normalized to a constant $^{13}\text{C}/^{12}\text{C}$ ratio (see e.g., Broecker and Peng, 1982). The equation used is as follows:

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

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

Carbon-13 (‰)

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

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

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

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