original Grand Tour Version 2 front page, with oxygen and silicate data plotted in volume units

A GRAND TOUR OF THE WORLD OCEAN - VERSION 2

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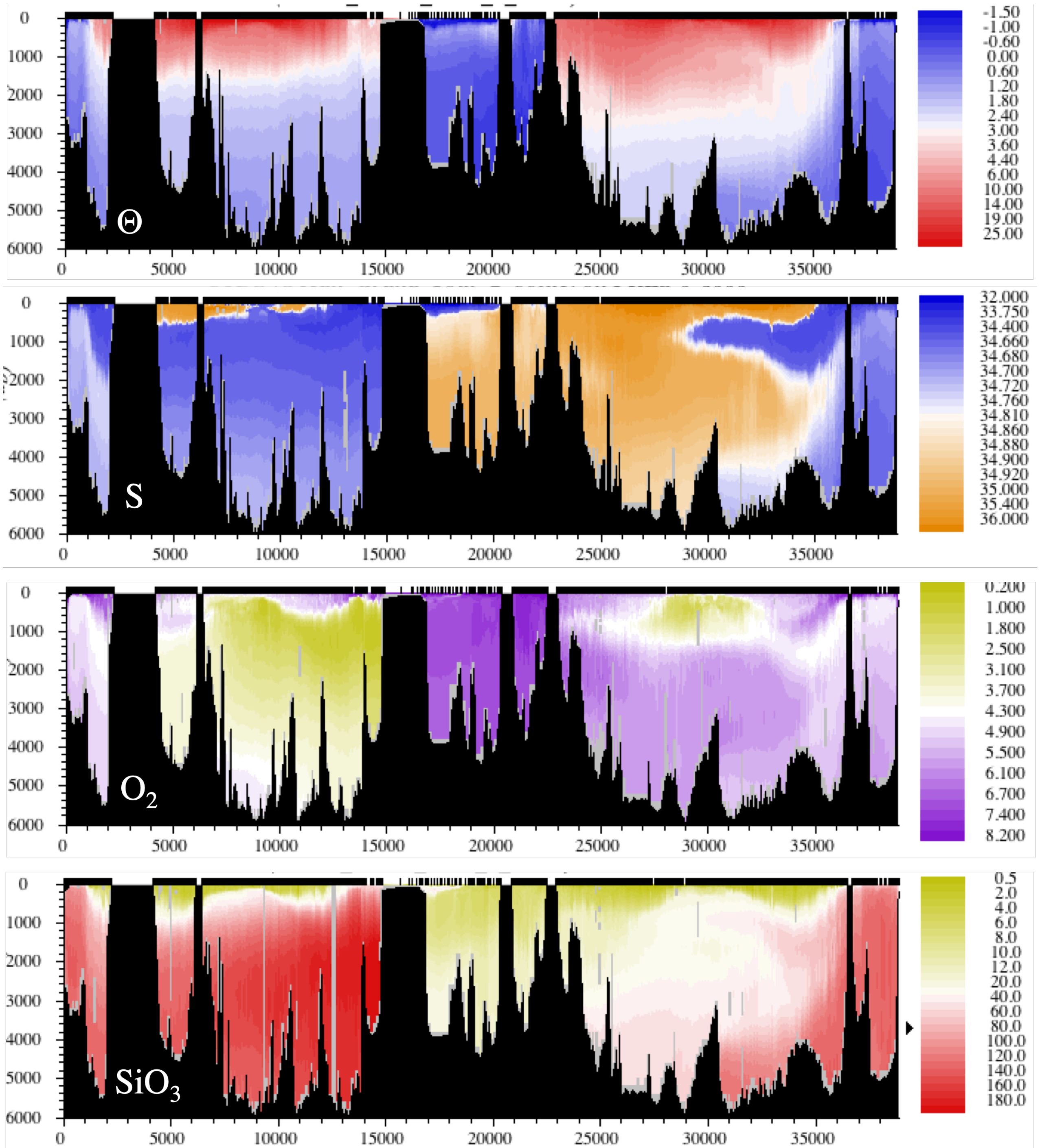

June 2009

"OCEAN GRAND TOUR 2" DOCUMENTATION

(*original 2009 "volume unit" text, with edits for 2022 "mass unit" version highlighted*)

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Introduction

Presented here is an edited collection of oceanographic CTD and bottle data files which, when assembled, create a transect of the ocean from the northwestern Ross Sea Antarctic continent north through the Pacific Ocean and Bering Strait, across the Arctic Ocean over the North Pole and through the Nordic Seas, south through the Atlantic Ocean, and ending at the Antarctic continent in the Weddell Sea. The data are included both assembled into the "Ocean Grand Tour 2" as Java OceanAtlas binary data files, and also as component pieces in both JOA binary and ASCII WHP-Exchange formats.

The original "A 'Grand Tour' Cross Section of the World Ocean" was conceived and constructed in late 1994 by Jim Swift and Eddy Carmack for a science poster illustrating how the recently completed CCGS Louis S. St-Laurent and USCGC Polar Sea "Arctic '94" Arctic Ocean transect from near Bering Strait to the Nansen Basin, over the North Pole, joined the oceanography of the Pacific and Atlantic Oceans. This was the introductory text on the original poster:

> "It has commonly been perceived that the Arctic Ocean is isolated from other oceans because it is remote, almost completely surrounded by land, and insulated by its permanent ice cover.
>
> "However, we see that the Arctic Ocean is connected to the Pacific by the 50-meter deep Bering Strait, through which it receives an inflow of low salinity, nutrient-rich water. It is connected to the Nordic Seas and the Atlantic by a much deeper (2600 meter) passage between Greenland and Spitsbergen, through which deep water exchanges take place. Cold, salty Arctic Ocean waters from below 200 meters move south through this passage, join with dense waters from the Nordic Seas, and flow into the Atlantic Ocean. Being denser than the resident Atlantic waters, they sink and spread southward as "new" North Atlantic Deep Water. Because these Arctic waters carry high oxygen concentrations from their recent contact with the atmosphere, they help "ventilate" the deep world ocean as they move southward.
>
> "We have illustrated the unique nature of Arctic Ocean waters and their relationships with other ocean waters with a "grand tour" of the ocean. Our cross section of ocean-water properties — like a vertical slice through the oceans — uses the Arctic '94 oceanographic data to link earlier data gathered from the Atlantic and Pacific oceans. Depictions such as this are clarifying the role of the Arctic Ocean as part of the global ocean system."

The 1994 global transect itself was sufficiently interesting that a page of sections made from it - illustrating potential temperature, salinity, sigma-0, sigma-3, dissolved oxygen, silicate, nitrate, and phosphate, along with a brief descriptive text - was printed as an oceanographic illustration and teaching aid. Appendix I contains the original documentation printed on the pages with the sections. We have included a PDF version of the one-page 1994 "Grand Tour" (file name: "Ocean_Grand_Tour_original.pdf") in the directory with the Grand Tour 2 materials.

In the intervening 15 years additional data were collected, software was upgraded, improved data formats came into use, and the author gained further experience. Constructing an "Ocean Grand Tour 2" seemed worthwhile.

Features/Improvements of the Ocean Grand Tour 2

Various new features and improvements were possible with the new version of the Ocean Grand Tour:

Preservation of distance

Here the term "preservation of distance" is used to mean that if the data are plotted with the offset between consecutive stations proportional to the distance between them, that a sensible plot ensues, without major gaps.

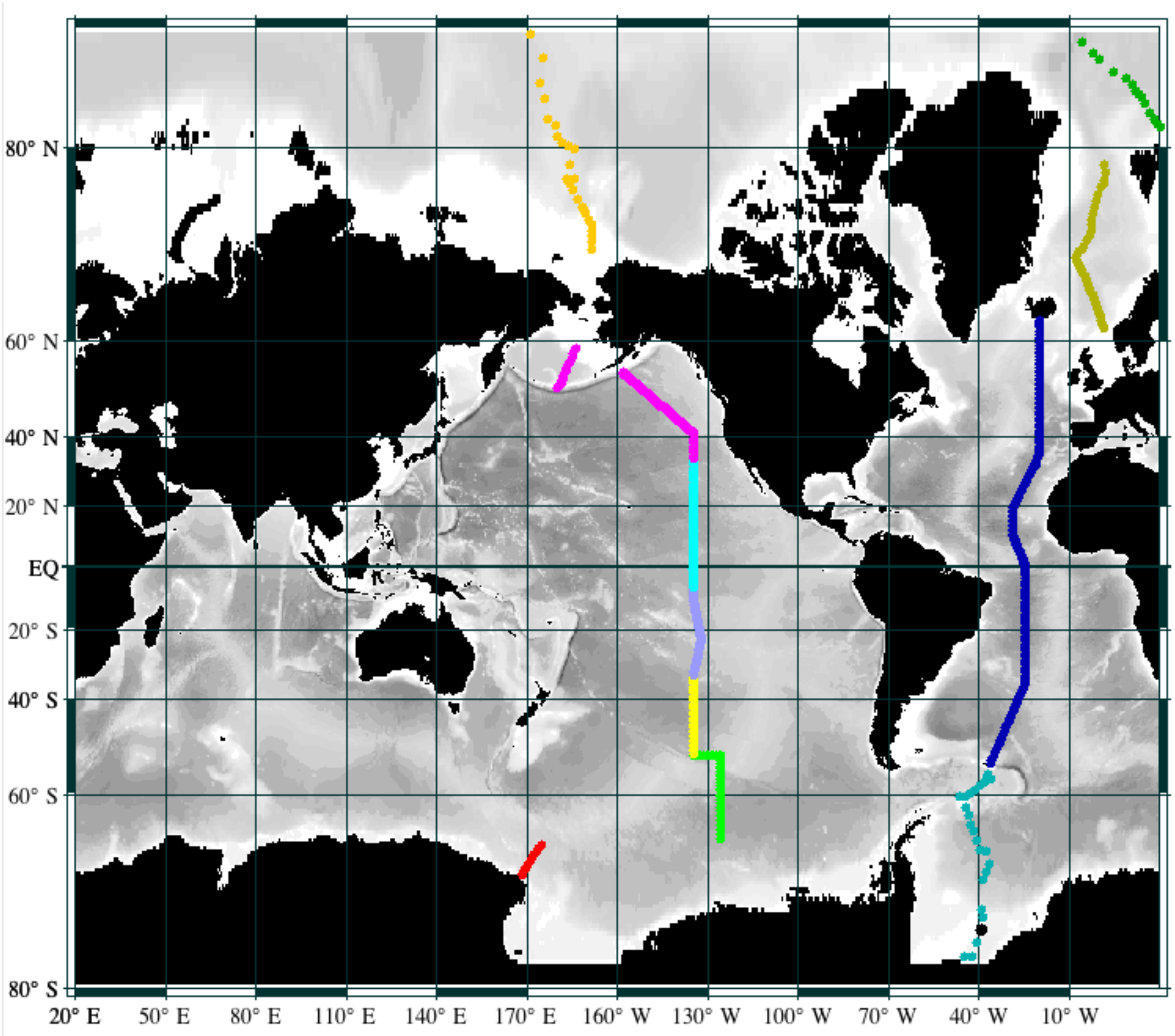
The original Grand Tour section (see figure below) had short data gaps and section offsets, especially in the Pacific Ocean. Although good quality data sets were available, it was not feasible with the data existing in 1994 to produce a continuous boundary-to-boundary meridional (south-north) Pacific section. The 150°W "P16" section was (and remains) excellent at illustrating the central Pacific Ocean water masses, though it did not connect well to the Antarctic continent or the Bering Sea stations from the northern end of the "P14" line. It was also not possible to produce a Nordic Seas section that would join an Arctic Ocean section with the "A16" 25°W Atlantic Section. To sidestep the limitations posed by these gaps, the stations in the original Grand Tour were plotted sequentially, with a pre-set spacing between successive stations, regardless of the distance between them or intervening land. This may seem a major transgression, but the fact remains that the original Ocean Grand Tour did illustrate the Pacific-Arctic-Atlantic distribution of water properties quite successfully.

Still, there are advantages to a distance-preserving section, and so for the Ocean Grand Tour 2 the "P14" Pacific section is used (see figure later in this document), because with the addition of a few stations near Antarctica from the "S4P" WOCE cruise, its pieces comprise a continuous, distance-preserving section from the Antarctic continent to the Bering Sea shelf break. And the 2002 Nordic Seas cruise provided a section from Iceland to Spitsbergen that joined the chosen Arctic Ocean section to the "A16" Atlantic section, again offering a sensible section when the offset between consecutive stations is proportional to distance.

Inclusion of land

Where land or shallow water is present between two joined sections (e.g., New Zealand, Spitsbergen, Iceland), artificial very shallow stations are added to the Ocean Grand Tour data sets so that the land appears in the plotted sections.

Figure: Map showing most stations of the original Ocean Grand Tour section.



Upgraded and additional data sets

New data came available which provided an improved data set for the Grand Tour section:

The "P14S" data set, which carries the "P14" line south to the "S4P" section, was not available in 1994.

The US Arctic Shelf-Basin Interactions (SBI) field program during 2002-2004 included a thorough survey of the Chukchi Sea shelf and slope region which provided an excellent means to join the P14 Bering shelf break stations to an Arctic Ocean section.

The Oden/Healy 2005 trans-Arctic section, though taking a different track than the 1994 trans-Arctic section, included nearly the full suite of parameters desired, including one the most extensive Arctic Ocean sections of CTD oxygen profiles yet made.

The 2002 Nordic Seas expedition by R/V Knorr and Icebreaker Oden included an Iceland-Spitsbergen transect that was nearly ideal for the Grand Tour 2, plus included nearly the full suite of parameters, including CTD oxygen profiles.

The "A16" line was redone in 2003 and 2005, providing a modern data set temporally matching the new Nordic Seas and Arctic Ocean data.

The "A23" data set, which carries the "A16" line south to the Antarctic continent, was not available in 1994.

Clean data sets

Although the data sets used in the original Grand Tour section were of high quality, the WOCE-type data sets deliberately contain their bad data (with a quality code indicating those data values are bad), there are extra bottle closed at some levels (for example for test purposes or to collect additional water for other parameters), and a few profiles suffer so many problems as to render them of little use. For this education-oriented data set, it was thus useful to further clean the data sets - i.e. removing bad or non-useful data.

Upgraded parameter list in bottle data files providing additional water properties

The original Grand Tour data set focused on only water properties most often sampled and used in older basin-scale ocean section studies: bottle temperature, salinity, dissolved oxygen, and nutrients (NO3, PO4, SiO3). These parameters were common to all the cruises used in that compilation. But the WOCE data had additional parameters, and the Arctic and Nordic Seas data from 2005 and 2002, respectively, also contained many of the same parameters. It was thus possible to add CFC-11, CFC-12, total dissolved carbon, and total alkalinity to the parameter list for the new Grand Tour 2 section.

CTD data files adding a CTD version,

No CTD-based data set was made for the original Grand Tour. A matching Grand Tour 2 section based on CTD data was constructed. The CTD data in Grand Tour 2 are highly decimated.

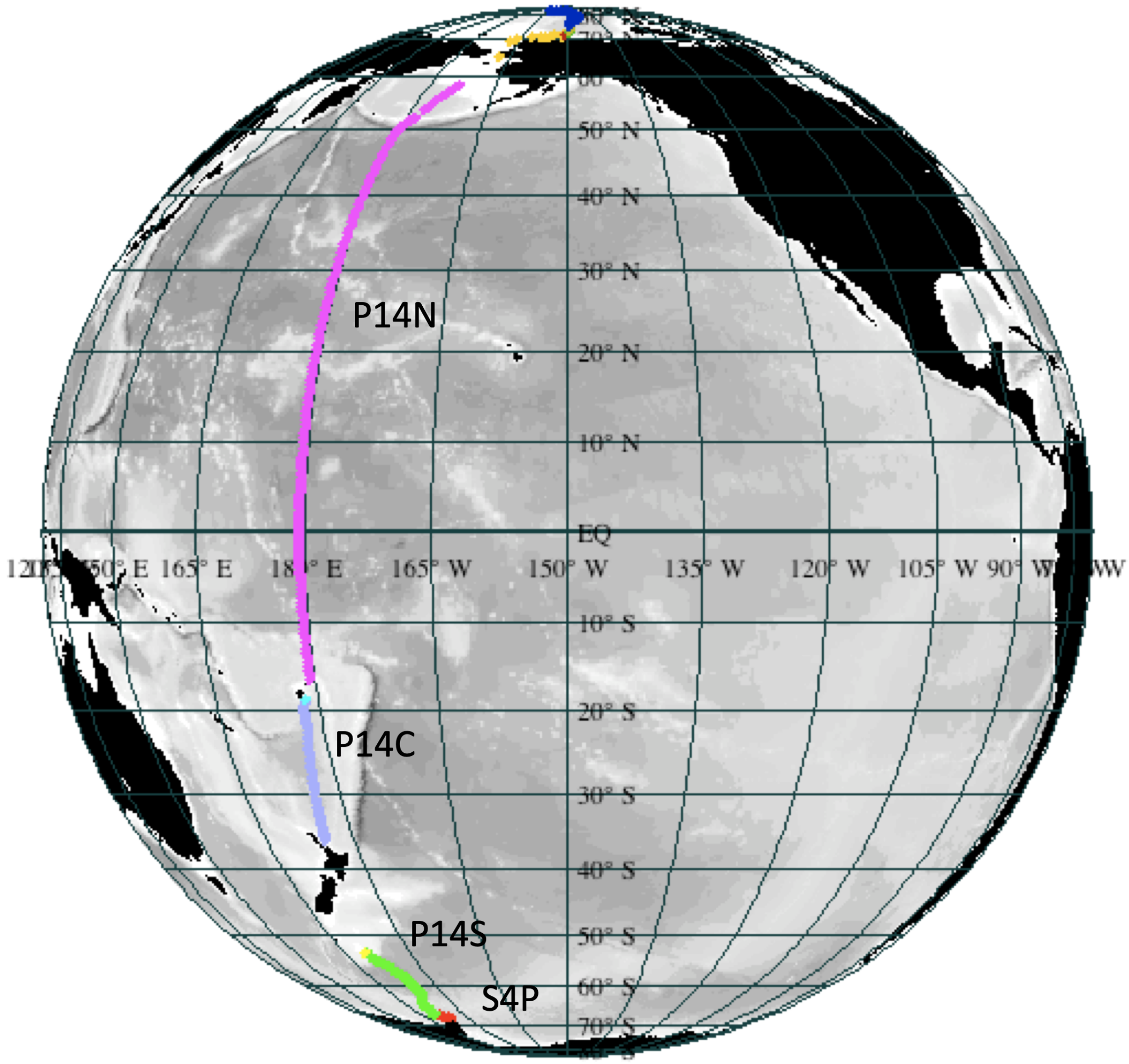
Providing the data in additional formats

The original Grand Tour data were supplied in OceanAtlas binary format only. To make it easier for the Grand Tour 2 data to be used in other software applications such as spreadsheets, plotting applications, and Ocean Data View, ASCII data sets are now also included for each cruise.

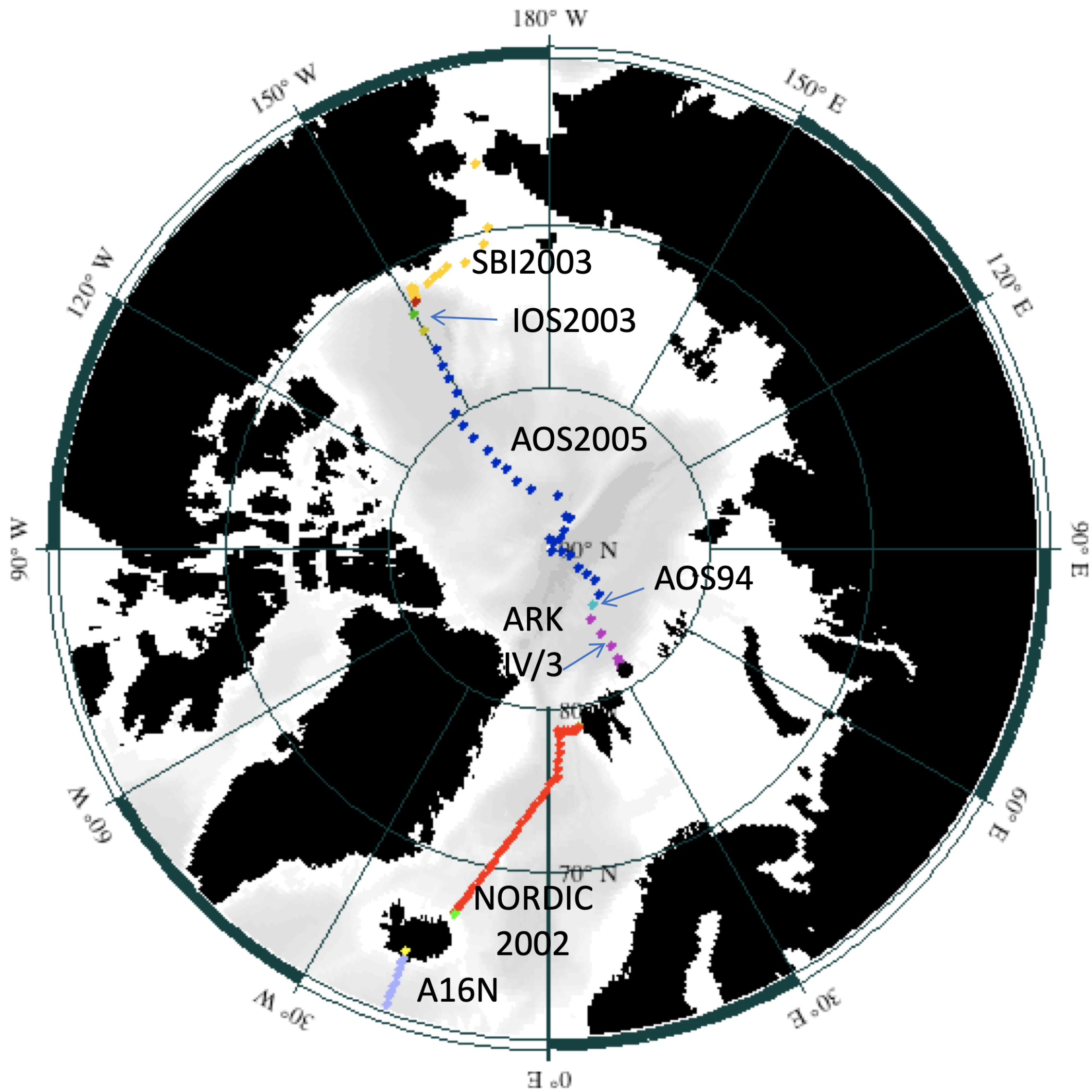
Maps Showing the Stations and Path of the Grand Tour 2

The three maps which follow show all stations used in the Grand Tour 2.

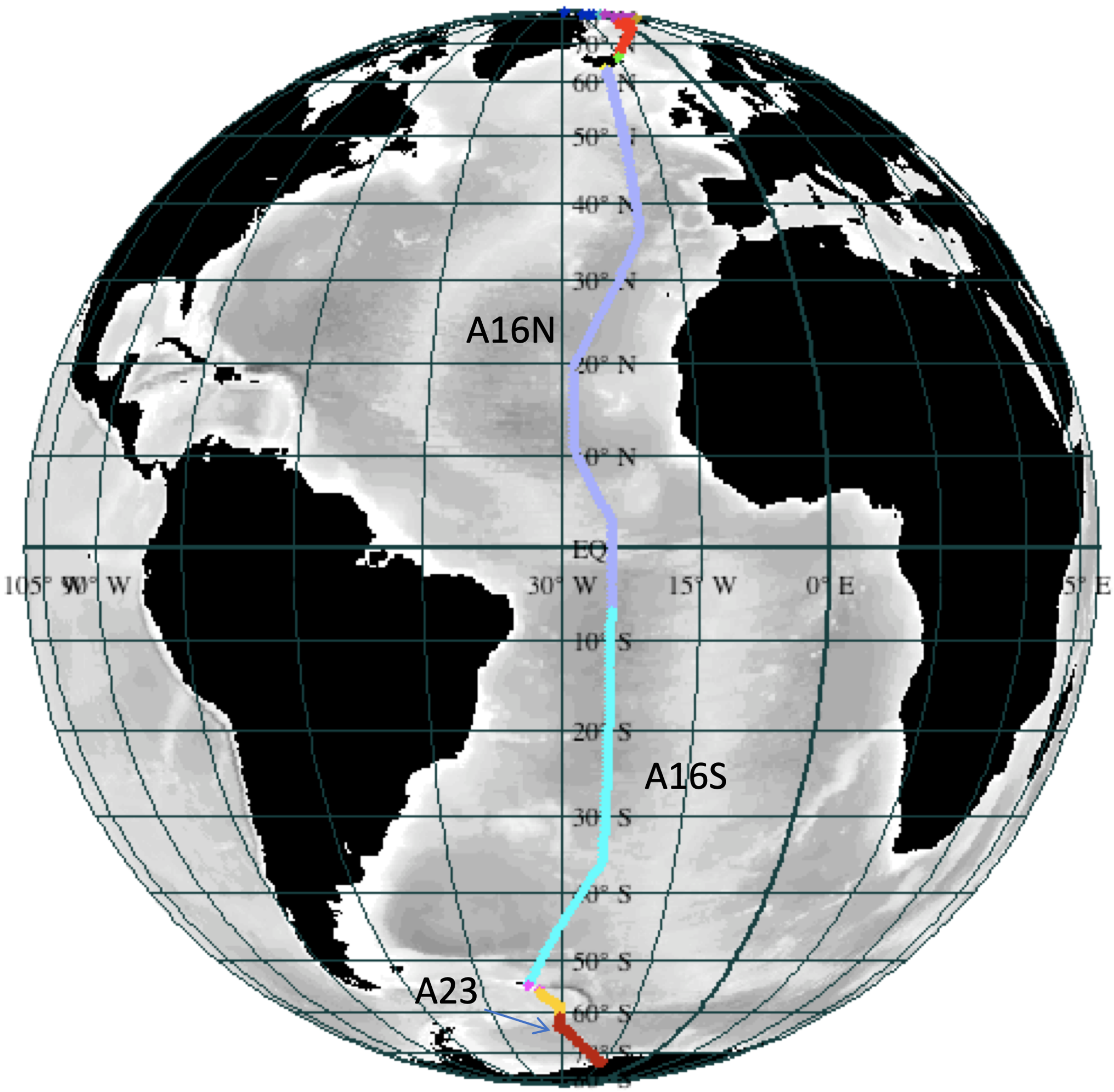
Map 1: Pacific Ocean



Map 2: Arctic Ocean and Nordic Seas



Map 3: Atlantic Ocean



Data Sources for Grand Tour 2

Data taken from the following cruises (in the order listed) were used to construct the Grand Tour 2 data files. Not all stations from each cruise were used (see "cruise-specific comments" below). CCHDO EXPOCODES are included for each cruise.

S4P 90KDIOFFE6_1; Mikhail H. Koshlyakov (Shirshov IO) and James G. Richman (OSU); 1992.02.14 - 1992.04.06; R/V Akademik Ioffe; Montevideo, Uruguay, to Wellington, NZ; 113 CTD/rosette stations.

P14S 31DSCG96_1; John Bullister and Gregory C. Johnson (NOAA/PMEL); 1996 JAN

05 to 1996 FEB 04; R/V Discoverer; Hobart, Tasmania, to Wellington, NZ; 29 CTD/rosette stations (the expedition also included P15S, with an additional 144 stations).

P14C 316N138_7; Dean Roemmich and Bruce D. Cornuelle (UCSD/SIO); 1992.SEP.01 - 1992.SEP.15; R/V Knorr; Auckland, New Zealand, to Suva, Fiji; 52 CTD/rosette stations.

P14N 325023_1 and 325024_1; Gunnar I. Roden, University of Washington; 1993.JUL.05 - 1993.AUG.11 and 1993.AUG.14 - 1993.SEP.01; R/V Thomas G. Thompson; Dutch Harbor, Alaska, to Tarawa, Republic of Kiribati, and Tarawa to Suva, Fiji; 185 CTD/rosette stations.

SBI Survey 320620030706 or 3206NBP03-04A; James Swift, UCSD/SIO; 2003 July 05 - 2003 August 20; RVIB Nathaniel B. Palmer; Dutch Harbor, Alaska, to Barrow, Alaska; 329 CTD/rosette stations.

AOS2005 77DN20050819 or 77DN200508; Anders Karlqvist, Swedish Polar Secretariat; 19 August - 25 September 2005; Icebreaker Oden; Barrow, Alaska, to Longyearben, Spitsbergen, Norway; 42 CTD/rosette stations.

IOS2005 (2 partial stations in bottle data file only; see below) 18SN20050729; Sarah Zimmerman, IOS/BC; 2005 July 29 - 2005 September 01; CCGS Louis S. St-Laurent; Cambridge Bay - Kuglugtuk, Canada; 40 CTD/rosette and 5 CTD-only stations.

AOS94 18SN19940724 or 18SNAO94; Knut Aagaard, NOAA/PMEL, and Eddy Carmack, IOS/BC; 1994 July 24 - 1994 September 09; CCGS Louis S. St-Laurent; Nome, Alaska, to Halifax, Nova Scotia; 39 CTD/rosette stations.

Arktis IV/3 06AQ19870704; Jorn Thiede, IFM Kiel, 1987 July 4 - 1987 September 2; PFS Polarstern; Tromso, Norway, to Hamburg, Germany; 25 CTD/rosette stations.

Nordic Seas 2002 316N20020530 or 316N166.11; James Swift, UCSD/SIO, and William Smethie, LDEO/Columbia; 2002 May 30 - 2002 July 1; R/V Knorr; Reykjavik, Iceland, to Glasgow, Scotland; 159 CTD/rosette stations.

A16N 33RO200306_01 and 33RO200306_02; John Bullister, NOAA/PMEL, and Nicolas Gruber, UCLA; 2003 JUN 04 - 2003 AUG 11; R/V Ronald H. Brown; Reykjavik, Iceland, to Natal, Brazil; 150 CTD/rosette stations.

A16S 33RO200501; Rik Wanninkhof, NOAA/AMOL, and Scott Doney, WHOI; 2005 JAN 11 - 2005 FEB 24; R/V Ronald H. Brown; Punta Arenas, Chile, to Fortaleza, Brazil; 121 CTD/rosette stations.

A23 74JC10_1; Karen Heywood, UEA, and Brian King, SOC; 1995.03.20 - 1995.05.06;

James Clark Ross; Stanley, Falkland Islands, to Rio de Janeiro, Brazil; 128 CTD/rosette stations.

Measured Parameters Utilized in the Grand Tour 2

Bottle data files

CTDPRS, CTDTMP, CTDSAL, SALNTY, CTDOXY, OXYGEN, SILCAT, NITRAT, NITRIT, PHSPHT, CFC-11, CFC-12, SF6, TCARBN, ALKALI

CTD data files

CTDPRS, CTDTMP, CTDSAL, CTDOXY

Note 1: Definitions of each of the parameters is found in the document "WHP_Exchange_Description_05June2008.pdf" which is included in the Ocean Grand Tour 2 directory.

Note 2: All of the measured parameters in the CTD data files, and all the measured parameters except CTDPRS and CTDTMP in the bottle data files, include WOCE Data Quality code "flags". (See "WHP_Exchange_Description_05June2008.pdf" for information about flag definitions. The most basic information is that flag "2" = "good".)

Note 3: When one of the listed parameters was not included in an original cruise data file, data columns filled with -999 (the missing data value) and data quality flag columns filled with 9 (parameter not measured) were added for that parameter.

Note 4: When additional parameters were present in an original data file, their data columns and any associated quality flag columns were deleted from the data file.

Note 5: The parameter columns were adjusted in all ASCII bottle or CTD data files so that the parameters were in the order listed above.

Note 6: Blank columns for SF6 and its quality code are included in the 2022 "mass" version to improve compatibility with the JOA Suite "clean" data sets.

Data processing notes

All bottle files

All data rows where the bottle quality code was "bad" or (WOCE quality code 4) were eliminated.

Most data rows where there were neither nutrient data nor dissolved oxygen data were eliminated.

Most rows which represented duplicate bottles - more than one rosette bottle closed at a given level - were eliminated, with the row containing the principal bottle parameter data retained.

All values for "bad" data (WOCE quality code 4), most "questionable" data (WOCE quality code 3), and most "Irregular digital chromatographic peak integration" CFC data (WOCE quality code 8) were replaced with the missing data value -999.

The original WOCE oxygen and nutrient data units of μMol/kg were retained in the WHP-Exchange bottle data files for all WOCE data.

For some of the Arctic cruises, oxygen and nutrient data were not available in WOCE μMol/kg mass units, but only in traditional volumetric ml/l (oxygen) and μM/l (nutrient) units. Please see the notes below for the individual cruises.

> *IMPORTANT: The Arctic Ocean and Nordic Seas data files used in this collection have their oxygen and nutrient data in traditional volume units (mL/l for oxygen and µM/l for nutrients) rather than the mass-based units (µMol/kg) used for oxygen and nutrients in the other data files. Therefore when using ~~the~~ any individual cruise ASCII data files from these cruises please be very careful that the application data import settings are appropriate for the cruise you are using. You may need to convert the Arctic/Nordic oxygen and nutrient data to mass units, or convert other data to volumetric units. This affects the following cruises: SBI Survey, Oden AOS2005, IOS 2005, AOS94, Arktis IV/3, and Nordic Seas 2002. The Java OceanAtlas binary data sets for all Grand Tour 2 cruises are in traditional volume units (mL/l and uM/l) for oxygen and nutrients, respectively.*

~~For the Java OceanAtlas binary files only, all oxygen and nutrient data were converted to volumetric units (ml/l for oxygen and μM/l for nutrients) when the data were read into binary.~~

For both the WHP-Exchange (suffix "_hy1.csv") and JOA binary (suffix ".joa") bottle data files in the "mass" version of the Ocean Grand Tour 2 bottle data, the dissolved oxygen (CTDOXY and OXYGEN) and nutrient (SILCAT, NITRAT, NITRIT, and PHSPHT") data are in mass units (μmol/kg).

Notes about the Cruise Data Files Supplied With Ocean Grand Tour 2

S4P In S-to-N order: Bottle data from stations 780-768, plus 781-783, are used in the Grand Tour 2. Some stations used for the Grand Tour 2 do not have CTD oxygen probe data. The cruise documentation online at the CCHDO discusses problems with the CTD oxygen probes in the cold conditions experienced. There were no total alkalinity data.

P14S In S-to-N order: Bottle data from stations 32-04 are used in the Grand Tour 2.

P14C In S-to-N order: Bottle data from stations 01-16 and 18-52 are used in the Grand Tour 2. There are no total dissolved carbon or total alkalinity data.

P14N In S-to-N order: Bottle data from stations 185-116, 114-32, 30-19, 17-14, 11-08, and 06-01 are used in the Grand Tour 2. There are no CTD oxygen sensor data (at bottle data levels) in the bottle data file.

SBI Survey In S-to-N order: Bottle data from stations 05, 14, 168, 152, 85, 93, 74, 64, and 53-41 are used in the Grand Tour 2. **Warning**: *The SBI Survey ASCII data files have dissolved oxygen and nutrient data in volume units, not mass units!* There are no CFC-11, CFC-12, total dissolved carbon, or total alkalinity data in the bottle data file. The first 8 stations in this part of the Grand Tour 2 section were pieced together mostly from multiple sections crossing one of the paths of the Pacific Water inflow to the Arctic Ocean through Bering Strait - the path leading to Barrow Canyon - then switching to an SBI section from the shelf to the basin interior (stations 53-41). The silicate signal was the principal guide to station choice, though there was also an effort to select stations from each cross-section with the densest water. The final stations of these 8 do not fit as well to the boundary-crossing section (stations 53-41) as well as might be liked, but the overall depiction of the connection between the Pacific Ocean and Arctic Ocean over the Chukchi Shelf and through Barrow Canyon is still useful.

AOS2005 In Alaska-to-Nansen Basin order: Bottle data from stations 05, 08, 09, 11, 12, 14, 15, 17, 19-21, 23, 25, 26, 30-33, 39, 41-44, 46, 47, and 49-51 are used in the Grand Tour 2. **Warning**: *The ODEN/IOS2005 ASCII data files have dissolved oxygen and nutrient data in volume units, not mass units!* This trans-Arctic section crossed the Canada Basin from south to north, and also provided a good section across the Amundsen Basin. Heavy ice conditions in the northern Makarov Basin caused some detours, and the crossing of the Lomonosov Ridge included bathymetric surveys and extra stations, so had to be pieced together. Due to heavy ice conditions the team was unable to complete the planned section across the Nansen Basin.

IOS2005 At AOS2005 stations 06 and 07 (in the southern Canada Basin), there were problems with the rosette, and so while there are CTD data from these stations, there are no bottle data above ca. 2000 meters from these two stations. It happened that scientists from the Institute of Oceanographic Sciences, Patricia Bay, Canada, occupied stations very near those two locations in 2005, and Fiona McLaughlin has given permission to include their data from those stations ("CB2" and "CB3" in S-to-N order) to complete this part of the bottle data file. **Warning**: *The ODEN/IOS2005 ASCII data files have dissolved oxygen and nutrient data in volume units, not mass units!* There are no CFC-11, CFC-12, total dissolved carbon, or total alkalinity data in the bottle data file.

AOS94 Only station 36 is used in the Ocean Grand Tour 2, in order to provide a link between the AOS2005 and Arktis IV/3 sections. **Warning**: *The AOS94 ASCII data files have dissolved oxygen and nutrient data in volume units, not mass units!* There are no total dissolved carbon or total alkalinity data in the bottle data file. The original Ocean Grand Tour was sparked by the AOS94 cruise data, and so this station also provides a historical placeholder. The AOS94 cruise track crossed the Makarov Basin, and provided an excellent crossing of the Lomonosov Ridge (neither of these are included here). CTD oxygen probes were used on AOS94 (albeit a more primitive device than is use today), and despite the extreme problems using these in cold conditions, several useful dissolved oxygen profiles were completed, one of which happened to be at station 36.

Arctic 87 In N-to-S order: Bottle data from stations 362, 358, 340 (see note following re "341"), 310, 296, 287, 285, 282, 280, and 278 are used in the Grand Tour 2. There are no CFC-11, CFC-12, total dissolved carbon, or total alkalinity data in the bottle data file. **Warning**: *The Arctic 87 ASCII data files have dissolved oxygen and nutrient data in volume units, not mass units!* The bottle oxygen data included here were corrected for a small offset noted when comparing the 1987 and 1994 deep water data. The ship was on station 340 for several days (due to a medical emergency), and carried out repeated hydro casts. A marked change in water properties was observed during this time, one mode "more like the boundary" and the other "more like the interior". The "interior" version was here artificially assigned station number 341. One must recall, however, that these data are from the era prior to the 1990s Atlantic layer warm event which affects many of the other Arctic Ocean data. The original CTD data for this cruise were lost by the German team who lead the CTD work. In the 1990s SIO graduate student Diana Lewis took the only extant copy - a decimated version of the CTD data - and applied basic CTD corrections based on the bottle data. There are no CTD oxygen sensor data. Neither the 1994 nor 2005 trans-Arctic sections were able to complete their planned scientific crossings of the Nansen Basin (in 1994 due to mechanical problems with the companion icebreaker and in 2005 due to heavy ice, low fuel, and short time). The landmark 1987 crossing of the Nansen Basin by PFS Polarstern remains the section of choice for the western end.

Nordic Seas 2002 In Spitsbergen-to-Iceland order: Data from stations 39-01 are used in the Grand Tour 2. **Warning**: *The Nordic Seas 2002 ASCII data files have dissolved oxygen and nutrient data in volume units, not mass units!*

A16N In N-to-S order: Bottle data from stations 01-39, 41-92, and 94-150 are used in the Grand Tour 2.

A16S In N-to-S order: Bottle data from stations 112-01 are used in the Grand Tour 2.

A23 In N-to-S order: Bottle data from stations 35-14 and 11-03 are used in the Grand Tour 2. There are only a few total dissolved carbon and no total alkalinity data in the bottle data file. All CTD oxygen sensor data were coded "3" (= uncertain or suspicious) and so are not included in the Grand Tour 2.

Appendix I - The original documentation printed with the 1994 sections

The global section and descriptive text places onto a single page the World Ocean and an 'Ocean 101' description. The section was assembled from 674 full-depth hydrographic profiles beginning northwest of the Ross Sea [WOCE section S4(P)], north through the Southeast Pacific [P17E, P17A, P17S], East Central Pacific [P17C], Northeast Pacific [P17N], and Bering Sea [P14N]. The section then crosses the Canadian Sector of the Arctic Ocean to the North Pole [Arctic '94], and the Eurasian sector to Fram Strait [Oden '91]. Following a Nordic Sea crossing [Hudson 82-001], the section follows ca. 25°W through the Atlantic Ocean (including several crossings of the Mid-Ocean Ridge) [A16], finally crossing the Weddell Sea [assorted file data]. There are offsets where section pieces do not meet, and so each station is offset a fixed amount from the next. Most stations are at 30-mile spacing so this usually is only a small distortion. The results show clearly the primary thermohaline regimes of the World Ocean in relation to source regions and bathymetry.

The Global Waters

The plot of potential temperature (potential temperature contains a small pressure-related correction to *in situ* measured temperature) shows what we expect for the surface waters: warmest in the tropics and coldest in the polar regions with an extension into the Nordic Seas of warm water from the Atlantic. Along with the plot of salinity this shows quite clearly that the North Atlantic Ocean is overall the saltiest and warmest of the oceans. The reasons for this are to some extent still debated but focus on geography: The Mediterranean Sea (not on this plot) takes relatively fresh surface waters in and returns very salty water to the Atlantic. And the Nordic Seas take in relatively salty surface waters, cool them, and return them at great density, filling the North Atlantic abyss with salty waters. Other factors include precipitation and circulation patterns.

The most obvious global deformation in the density field is the huge upward adjustment in the Antarctic region where the Antarctic Circumpolar Current runs from west to east around Antarctica. The deep isopleths are compelled by the field of motion and the earth's rotation to rise close to the surface around Antarctica, where they are cooled and exchange gases. A huge tongue of relatively fresh Antarctic Intermediate water intrudes from the Antarctic into the South Atlantic at ca. 1000 meters. A similar but less dramatic tongue in the South Pacific does not show in salinity with this color scheme. A slightly more subtle deformation in the density field is seen in the bowl shaped regions of less dense water in the upper layers in the subtropics of each of the oceans:

At any given level the densities of the Arctic Ocean and Nordic Seas are the greatest in the World Ocean. This occurs primarily because already-salty surface waters enter the Nordic Seas and are cooled there, so the unique combination of cold and salt makes them very dense. They can sink to the bottom there, but the Greenland to Scotland Ridge retains the densest waters north of Iceland. Some very dense, cold, salty water does spill out. Where the overflows abut the remnants of Antarctic-source bottom waters in the North Atlantic these mix to form the lower North Atlantic Deep Water.

Where the salt carried by North Atlantic Deep Water influences the Antarctic circumpolar waters, and in turn where these relatively salty waters are brought near the surface by the patterns of circulation (for example in the Weddell Sea), the Antarctic forms its densest waters, aided by shelf processes there that provide extremely cold waters. The present vigor of the thermohaline circulation seems to owe much to the North Atlantic.

The dissolved oxygen section is useful to better understand ventilation. Cold surface waters can absorb more oxygen than can warm waters, so surface oxygen concentrations are highest in the polar regions. Convection of the surface waters in the Nordic Seas has at times reached to the bottom in the Greenland Sea. Thus within the Nordic Seas and Arctic Ocean the entire water column exhibits high concentrations of dissolved oxygen.

When this water spills over the Greenland-Scotland Ridge, it carries its high oxygen concentrations into the deep North Atlantic, where with other high oxygen dense waters (mostly from the Labrador Sea) and mixed-in bottom waters of Antarctic origin it forms the huge mass of high-oxygen North Atlantic Deep Water. This water spreads south into the South Atlantic and contributes high oxygen and high salinity to the Antarctic circumpolar region, traceable even to the South Pacific (note on the salinity section the very deep tongue of slightly higher salinity water — the lighter blue color — in the far South Pacific). The North Atlantic Deep Water thus refreshes or ventilates the deep World Ocean layer from about 1500-3000 meters.

But note the near-bottom tongues of dense water extending into the Atlantic and Pacific from the Antarctic. Although the Antarctic upper layer waters are as a whole relatively fresh, some are saltier than others and when they get very cold they can become quite dense. These are less severely restricted by submarine ridges in spreading north than the Arctic deep waters are in spreading south, so much of the abyssal World Ocean is filled from the densest available Antarctic waters. And the Antarctic Intermediate Water is a very important ventilator at its level of the oceans.

Where phytoplankton thrive they use up dissolved nutrients (such as nitrate, phosphate, and to some extent silicate) and produce oxygen. So the surface waters can become very low in nutrients and very high in oxygen. When these or other organisms die and decay, the process yields nutrients, which redissolve, and uses up oxygen. This decay often takes place in the subsurface waters, and so subsurface waters under and/or downstream from some productive regions can become very high in nutrients and very low (near zero concentrations) in dissolved oxygen. Mostly the siliceous organisms thrive in cold waters and so are more common in the polar regions, where their exoskeletons rain out of the upper layer to redissolve underneath or to join the sediment, which also re-dissolves into the ocean waters.

Recalling that the deep North Pacific is the farthest removed from the surface-generated sources from the Nordic Seas and the Antarctic, it is no surprise that the concentrations of these nutrients are highest in the deep North Pacific. The large proportion of siliceous organisms there and the high productivity of some North Pacific regions combine to generate a huge silicate tongue in the deep North Pacific. In contrast, the North Atlantic, though exhibiting some deep nutrient enrichment, is well ventilated by high oxygen, low nutrient surface waters convecting deep in the Nordic Seas and overflowing the Greenland-Scotland submarine ridge, so average nutrient concentrations in the North Atlantic Deep Water are much lower than in the deep Pacific Ocean. As the dense northern waters spread south the nutrient concentrations increase by regeneration and by mixing with Southern source waters.

[Note: Anthropogenic substances such as CFCs are proving useful for improving estimates of time scales related to the global circulation and exchanges. With the WOCE section data (see http://whpo.ucsd.edu), F-11, F-12, tritium, and helium sections can be generated with Power OceanAtlas (see http://odf.ucsd.edu/OceanAtlas).   Also illuminating are OceanAtlas plots of nutrient ratios (e.g., NO/PO) and of the relative contributions of temperature and salinity to density ($\alpha \bullet dT/dz$ and $\beta \bullet dS/dz$).

This was prepared with "Power OceanAtlas 1.0" and "Canvas 3.5.5" running on a Macintosh 7500 computer. The poster was plotted from the Mac on an HP DesignJet2500CP plotter. Contact Jim Swift for more information.]