

Atlases Give Global Snapshot of Oceans in the 1990s

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The comprehensive World Ocean Circulation Experiment (WOCE) survey of physical and biogeochemical observations, conducted between 1990 and 1998, was unprecedented in spatial coverage, accuracy, and types of measurements. WOCE data represent the “state of the oceans” during the 1990s, providing a baseline for changes that have been observed subsequently through repeats of selected WOCE sections via the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP; <http://www.go-ship.org>).

Today, more than a decade later, WOCE data continue to provide essential insights into the ocean’s role in the climate system. Further insights will be aided by a recently completed series of atlases based on data collected by the WOCE Hydrographic Programme (WHP), the largest element of WOCE. These atlases (<http://woceatlas.ucsd.edu>; see selected images in Figure 1) give the scientific community a graphical representation of global distributions of many chemical species and nutrients that were present within the ocean during the last decade of the last millennium. Armed with these, scientists can see at a glance the regional and vertical variations in properties associated with all of the major features of the ocean circulation; the large-scale effects of biological processes; and evidence of ocean exchanges with the atmosphere, cryosphere, and solid Earth.

WOCE at a Glance

The concept of WOCE originated in the late 1970s [*National Academy of Sciences*, 1983], following the first use of satellite altimeters to monitor sea surface topography. WOCE developed new instrumentation and ocean state estimations, setting the stage for 21st-century global observing systems, including the Argo profiling float and surface drifter arrays [*Siedler et al.*, 2013].

Comparisons between GO-SHIP and WOCE data have been used to show how the ocean

has evolved since the 1990s. The ocean is warming, taking up 93% of the excess heat in the entire Earth system. Of this, more than 30% of the total is in the abyssal ocean below 700 meters, and 16% is in the ocean below 2000 meters;

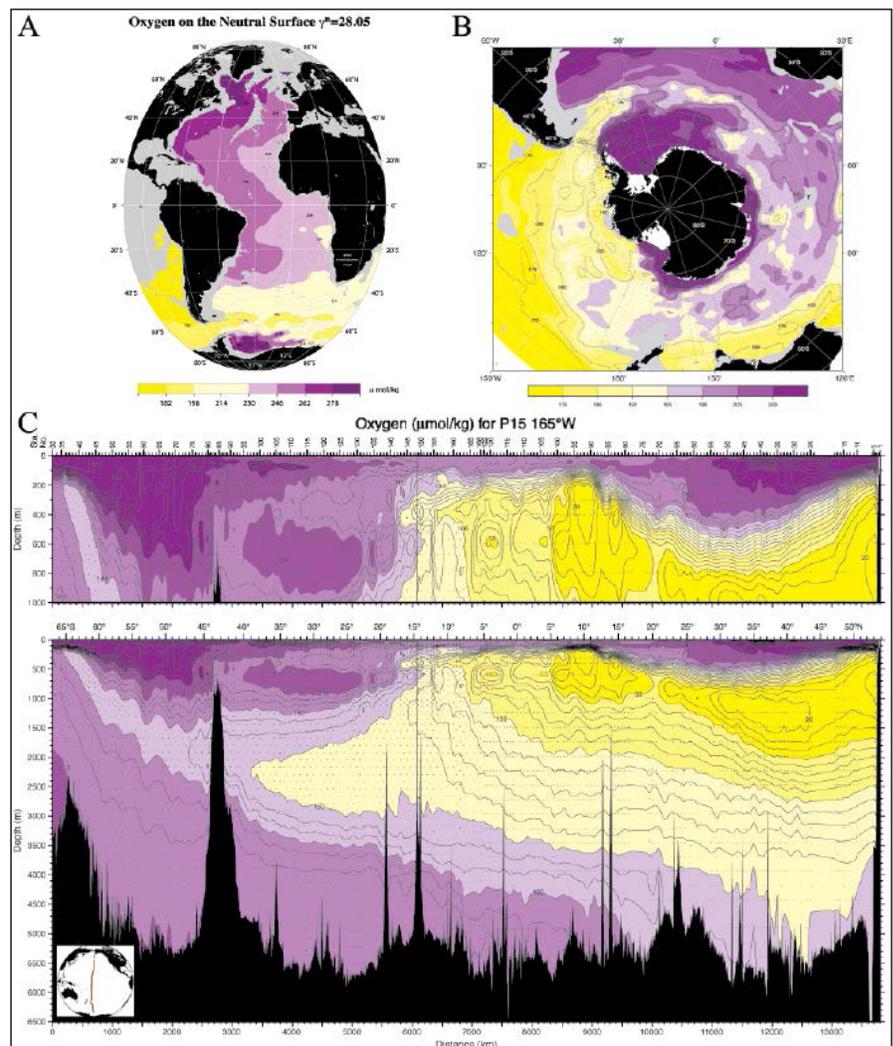


Fig. 1. Oxygen, measured in micromoles per kilogram ($\mu\text{mol/kg}$) on a specific neutral density surface ($\sigma_t = 28.05$ kilograms per cubic meter), in (a) the Atlantic Ocean [Koltermann et al., 2011] and (b) the Southern Ocean [Orsi and Whitworth, 2005], illustrating the southward spread of high-oxygen North Atlantic Deep Water (NADW) in the western Atlantic and spiraling of the NADW tongue around and toward Antarctica, with oxygen declining along the pathway. Lowest oxygen arises from the Pacific and Indian oceans. Newly ventilated high-oxygen Weddell Sea Deep Water is close to Antarctica. (c) Meridional section of oxygen ($\mu\text{mol/kg}$) through the central Pacific at 165°W , illustrating the well-ventilated oxygenated bottom and thermocline waters in the south, separated by the much older low-oxygen Pacific Deep Water from the north that rises up toward the sea surface in the Southern Ocean [Talley, 2013]. These and the hundreds of similar images in the World Ocean Circulation Experiment (WOCE) Hydrographic Programme (WHP) atlases give a snapshot of the state of the oceans in the 1990s.

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warming is concentrated in the Southern Ocean [Purkey and Johnson, 2010; Intergovernmental Panel on Climate Change, 2013]. Anthropogenic carbon uptake by the ocean has been mapped, and its effect on global carbon budgets has been quantified [Sabine et al., 2004; Khatiwala et al., 2013]. The oceans are acidifying [Feely et al., 2004].

WOCE and GO-SHIP data also show that oxygen concentrations are declining in the thermocline and tropical oxygen minimum zones are expanding [e.g., Stramma et al., 2008; Helm et al., 2011]. Upper ocean waters flowing from the Southern Ocean contain high-nutrient Pacific and Indian deep waters (e.g., Figure 1c), fertilizing three quarters of the ocean's biological productivity north of 30°S [Sarmiento et al., 2004]. The pathways of northern deep waters through the Southern Ocean spiral southeastward and upward (e.g., Figures 1a and 1b), affecting ice sheet mass balance where they reach the Antarctic shelf in the Amundsen Sea [e.g., Jacobs et al., 2013].

WHP in Detail

As part of WOCE, the WHP provided the first global, full water column distributions of dissolved inorganic carbon, alkalinity, chlorofluorocarbons, tritium, helium, and carbon isotopes ($\delta^3\text{He}$ and $\Delta^{14}\text{C}$), as well as the more conventional temperature, salinity, oxygen, and nutrient observations, from roughly 10,000 stations. A further 15,000 stations yielded a reduced suite of measurements for variability studies. These measurements were taken over roughly 10 years. The task required principal investigators and technical teams from more than 10 countries, aboard almost all the world's oceangoing research vessels.

The WHP observations, together with subsequent GO-SHIP repeat sections, have become the standards for comparing and calibrating other observations. WHP and GO-SHIP data will remain available through the Climate Variability and Predictability Experiment (CLIVAR) and Carbon Hydrographic Data Office (CCHDO; <http://cchdo.ucsd.edu>) and the Carbon Dioxide Information Analysis Center (CDIAC; <http://cdiac.ornl.gov>). Working together, CCHDO and CDIAC have set the highest standards for hydrographic data archiving, quality control, and access.

Hardbound and Online Atlases of WHP Observations

The WHP observations are presented graphically in a newly completed series of atlases [Sparrow et al., 2005–2013] of the Southern, Pacific, Atlantic, and Indian oceans (see Orsi and Whitworth [2005], Talley [2007], Koltermann et al. [2011], and Talley [2013], respectively; see also <http://woceatlas.ucsd.edu>). Vertical sections of the observed chemical and physical parameters along all of the WHP sections compose most of the color plates (e.g., Figure 1c). Maps of these observed water properties show the horizontal structures of these fields (e.g., Figures 1a and 1b), and

property-property plots illustrate the covariation of properties along each section.

DVDs and large-format print volumes are available from the authors (see website for information). The website provides all images for use in publications and presentations. Additional supporting information in the online version of this article shows the locations of all WOCE sections and further examples of each plot type.

In a complementary effort, the eWOCE online atlas (<http://www.ewoce.org>) [Schlitzer, 2002] provides a gallery of WHP sections and convenient access to plotting WHP data, as well as other data sets and climatologies, using the Ocean Data View display interface (<http://odv.awi.de/>).

A three-dimensional gridded climatology of temperature, salinity, oxygen, and nutrients was constructed from the WHP and historical data. This WOCE Global Hydrographic Climatology (WGHC; http://icdc.zmaw.de/woce_climatology.html) [Gouretski and Koltermann, 2004] was used for the WHP Atlantic atlas maps and for calculations of neutral density [Klocker et al., 2009] and thermodynamic properties of seawater [Intergovernmental Oceanographic Commission, 2010].

The comprehensive graphical presentation in the WHP atlases of measured ocean properties provides an excellent entree for validation of large-scale ocean and climate models, interpretation of climate-related ocean changes, and planning for ocean basin-scale experiments.

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