Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) provides key climate-relevant deep ocean observations

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The roles of the deep ocean in two critical aspects of climate, Earth's energy imbalance (heat and freshwater) and its carbon cycle, are reviewed in the introductory article in this issue of *Variations* (see Johnson and Winton), with particular attention to responses to anthropogenic forcing. In addition to its carbon content (hence acidity), the biogeochemistry of the deep ocean, including its oxygen and nutrient distributions, is also changing as a result of anthropogenic forcing, on top of large natural variability. Understanding of the present state and time variability of the ocean circulation, as well as distributions of temperature, salinity, and biogeochemical water properties including carbon, is essential for understanding both natural and anthropogenic climate change. For climate studies involving any of these variables, measurements over many decades of the highest accuracies are required. Observations such as these are central to climate syntheses such as those carried out by the Intergovernmental Panel on Climate Change (IPCC; e.g., Rhein et al. 2013; Ciais et al. 2013).

WOCE, CLIVAR, and GO-SHIP

For the deep ocean — defined here as deeper than the 2000 m sampling limit of conventional Argo floats — the primary comprehensive sets of oceanographic water property measurements over the past few decades that can be accurately compared and examined for trends are collected from research ships. The primary modern global-scale, ship-based survey was completed as part of the World Ocean Circulation Experiment (WOCE) during the 1990s. During the first decade of the new millennium, key subsets of these sections were repeated as part of CLIVAR. Repeats of core transects continue to the present, now under the auspices of the international Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP), which has commenced the second decadal re-survey as part of the Global Ocean Observing System (Figure 1).

GO-SHIP and its core requirements for measurements and accuracy are described on its website and in the supplements to a recent review (Talley et al. 2016). Each cruise must sample the ocean from the surface to within ~10 m of the bottom, generally from coast to coast and with a nominal station spacing of 55 km (0.5° latitude) or less to resolve mesoscale eddies and currents. Required measurements that are Essential Ocean Variables (EOVs) and/or Essential Climate Variables (ECVs) include physical (temperature, salinity, pressure, velocity), biogeochemical (dissolved oxygen, dissolved nutrients, inorganic carbon system parameters, dissolved organic matter), and transient tracers (chlorofluorocarbons, sulfur hexafluoride). Additional suites of measurements are routinely included.

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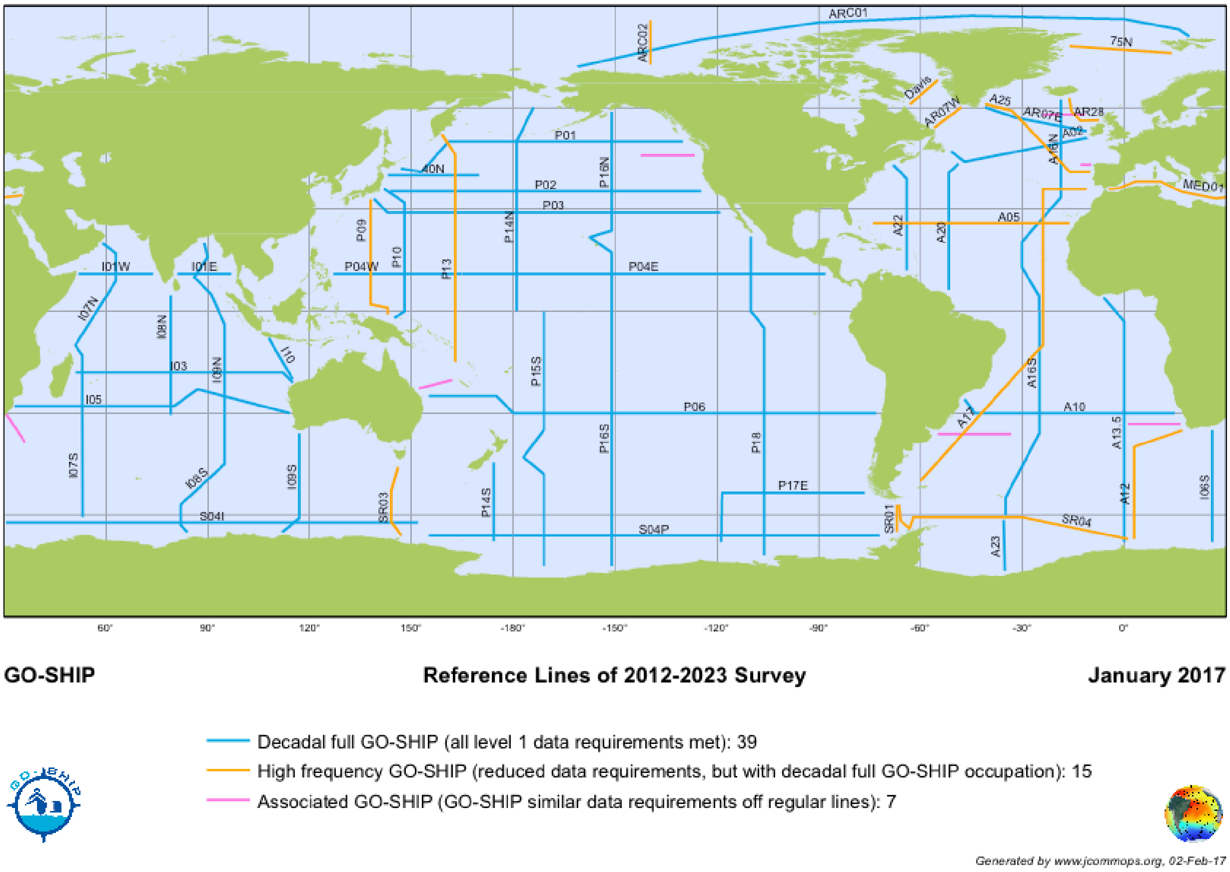

Figure 1. Location of GO-SHIP reference sections for the second repeat of the global decadal hydrographic survey during 2012–2023 (website, accessed 19 April 2017).

In addition to inventories of heat, freshwater, and dissolved gasses and chemicals, GO-SHIP and its predecessors also provide information on timescales of deep ocean ventilation through transient tracers, such as chlorofluorocarbons, sulfur hexafluoride, and carbon-14, as well as direct velocity and diffusivity-related measurements. The velocity and diffusivity measurements are important for examining ocean circulation and variability that affect water property distributions and transport heat, freshwater, and carbon around the planet.

Major results from analyses of the repeat hydrographic section data collected since the 1980s by these efforts are summarized in a review celebrating the first decade of GO-SHIP (Talley et al. 2016), to which the reader is referred for more information and results.

Heat

Earth's energy budget is out of balance owing to the continued buildup of greenhouse gasses in the atmosphere. More energy is entering than exiting at the top of the atmosphere, and the ocean, with its large mass and high heat capacity, absorbs the bulk of that energy. An observation-based analysis of this imbalance from 1971-2010 (Rhein et al. 2013) estimates that the ocean absorbed about 93% of the total excess energy, with 29% of the warming found below 700 m depth. Estimates for 1972–2008 show that warming below 2000 m accounts for 19% of the total (Talley et al. 2016). For the most recent decade, 2005–2016, warming below 2000 m accounts for 10% of the total ocean warming (Johnson et al. 2016; Johnson and Winton this issue), because the estimate of the ocean warming above 2000 m increased owing to the global sampling of Argo floats. Deep Argo, also discussed in this issue (Zilberman and Roemmich), will allow annual and improved decadal estimates of deep ocean warming when global coverage is achieved.

Warming of the upper ocean is occurring almost everywhere with stronger trends in the subtropical gyres and northern North Atlantic (Rhein et al. 2013). In contrast, the deep ocean is warming fastest in the Southern Ocean near Antarctic Bottom Water (AABW) ventilation sites with a smaller, but still significant deep warming signal to the north (Figure 2). Long-term cooling trends at mid and bottom depth are seen in the deep basins of the North Atlantic ventilated by North Atlantic Deep Water (NADW). This cooling has been attributed to natural decadal climate variability in the Labrador and Greenland Seas, which results in decadal changes in NADW properties and formation, and has obscured any possible long-term warming trend (e.g., Yashayaev and Loder 2016). Deep cooling is also observed in the East Indian Ocean; however, these trends are based on significantly less data compared to other basins and are not statistically significant. This Southern-Northern Hemisphere asymmetry was surprising when reported by Purkey and Johnson (2010), because the vigorous formation of NADW, which dominates the deep North Atlantic, was expected to have a much stronger climate signature than formation of AABW, which occurs at the freezing point.

Freshwater

GO-SHIP and WOCE salinity measurements have revealed a decades long freshening of the abyssal Southern Ocean, which is especially pronounced in the Australian and Ross Sea sectors (Swift and Orsi 2012; Purkey and Johnson 2013; Katsumata et al. 2015). This change has been associated recently with variations in Antarctic sea ice (Haumann et al. 2016), although increased ice shelf meltwater is also considered to be a factor (Jacobs and Giulivi 2010), with related iceberg calving dominating freshening in the Australian Antarctic Basin after 2007 (Menezes et al 2017).

We are not aware of analyses of global abyssal salinity changes from GO-SHIP and WOCE data that are similar to the deep temperature change analysis of Purkey and Johnson (2010). As an example of one of many regional comparisons, in the north where NADW is produced through deep convection, such as in the Labrador Sea, changes in upper ocean salinity affect its formation.

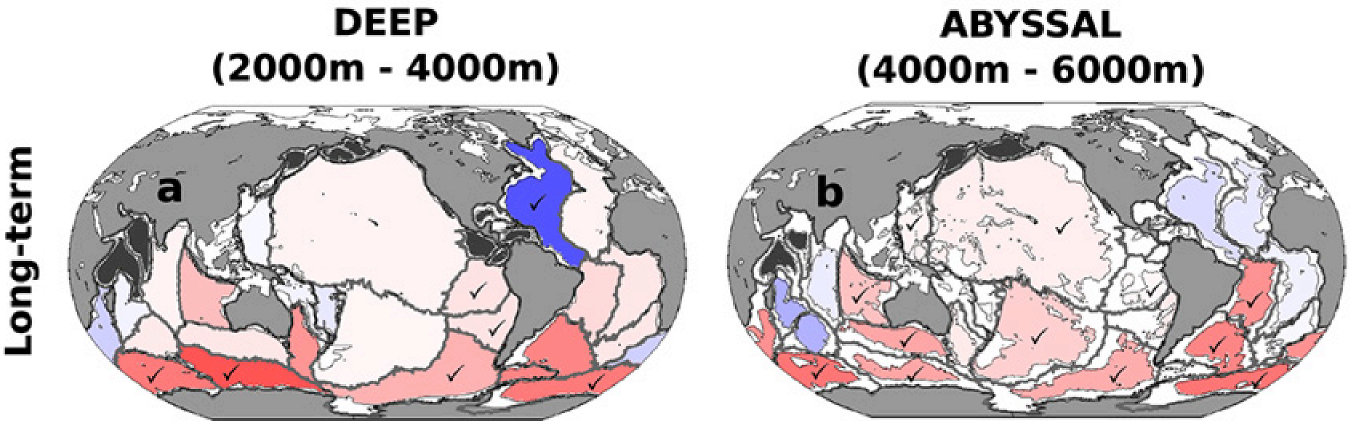

Figure 2. Deep (left, 2000–4000 m) and abyssal (right, 4000–6000 m) ocean heat content trends (in W m^{-2}) over 1991–2010, from Desbruyères et al. (2016), based on WOCE and GO-SHIP shipboard hydrographic data that spans each deep basin. Check marks indicate that the trend in a deep basin is statistically different from zero at the 95% level. The abyssal map is similar to that presented by Purkey and Johnson (2010) and modified for Rhein et al. (2013), also based on WOCE and GO-SHIP data.

When surface salinity decreases, as it does periodically and mostly driven by natural climate variability (North Atlantic Oscillation), the resulting increased stratification is overcome only when surface temperature is colder, leading to colder, fresher deep convection (Kieke and Yashayaev 2015; Yashayaev and Loder 2016). For the most recent decade, Argo float observations provided the most detailed information, but to connect this to the underlying deeper water properties, and to look at a multi-decade record, research ship observations have been required. These have included the repeated GO-SHIP sections across the Labrador Sea.

Carbon

For the Earth's carbon budget, GO-SHIP and its predecessors are the primary source of high-quality, global, full water-column ocean carbon data. Changes in ocean carbon inventory and mapping/inventory of anthropogenic carbon extensively use GO-SHIP and WOCE data. The GLODAPv2 synthesis product (Lauvset et al. 2016; Olsen et al. 2016) provides the most recent quality controlled ocean carbon datasets and mapped products, including all GO-SHIP data through 2012.

Based on these inventories and several independent approaches to quantify the amount of carbon that is due to anthropogenic increases, approximately 27% of the net carbon released to the atmosphere by fossil fuel burning and land-use change is sequestered in the ocean, with an increase in the rate of anthropogenic carbon uptake from 2.2 ± 0.5 Pg C yr^{-1} during the 1990s to approximately 2.6 ± 0.5 Pg C yr^{-1} during the most recent decade from 2005 to 2014 (Feely et al. 2016). Most of this increased carbon uptake is in the upper ocean, but some anthropogenic carbon is clearly penetrating to the deep ocean, well below 2000 m in the North Atlantic and Southern Ocean, associated with NADW and AABW ventilation (Khatiwala et al. 2013). Penetration of additional dissolved inorganic carbon (DIC) to the ocean bottom between WOCE and GO-SHIP transects over 20 years has been demonstrated, using a combination of carbon and chlorofluorocarbon (CFC) measurements (Figure 3; Wanninkhof et al. 2013a).

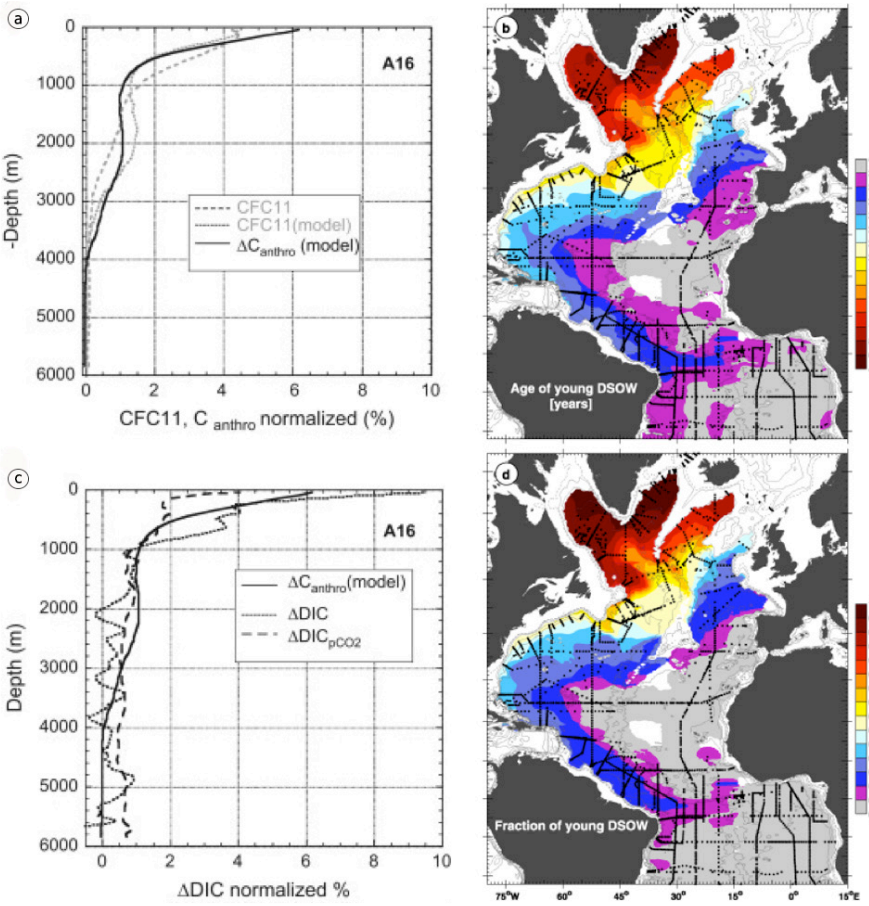

Figure 3. Left: Carbon and CFCs along GO-SHIP section A16 in the Atlantic (see Figure 1 for location; Wanninkhof et al. 2013a). (a) CFC profiles and modeled anthropogenic carbon (C_{anthro}), averaged between 63°N and 56°S. (c) Change in DIC from 1989 to 2005 (measured and based on pCO_2). Right: (b) Age and (d) fraction of NADW originating from the Denmark Strait Overflow Water (DSOW) between Greenland and Iceland based on CFC measurements; "young" means DSOW with measurable CFCs; from Rhein et al. (2015).

Deep ocean ventilation timescales

Transient tracers measured by WOCE and GO-SHIP and other associated research expeditions are providing invaluable information about the pathways and rates of the penetration of surface waters into the interior of the ocean. The tracer set that has emerged as central for GO-SHIP measurements is the suite of CFCs and more recently sulfur hexafluoride, all of which are purely anthropogenic, have well-known atmospheric time histories, and can be very accurately measured. A deep ocean analysis based on all available CFC datasets including those from GO-SHIP (Figure 3; right panels; Rhein et al. 2015) illustrates the rate of ventilation in the densest part of the NADW through the northern North Atlantic and exiting to the south along the western boundary and entering the South Atlantic, along with the age of the water since leaving the surface far to the north. Analyses of CFCs also document the formation rates and spread of AABW (e.g., Orsi et al. 1999, 2002). These and similar calculations provide important information for climate modeling, particularly those that are balancing northern and southern sources of deep and bottom waters. CFC inventory changes in the North Atlantic and Weddell Sea have also provided valuable information on the variability of the local production rates in the NADW and AABW (Rhein et al. 2011; Huhn et al. 2013).

Dynamical properties

GO-SHIP investigators routinely collect direct velocity observations, and the hydrographic data are analyzed to compute traditional geostrophic velocity and transport estimates. Section-integrated transports provide important information on the overturning circulation and its variability. This information includes estimates of the formation rates of the deep and bottom water masses that are ventilated from the surface (AABW and NADW) and of those that are created by upwelling of deep waters balanced by downward diffusion of buoyancy (heat) at low latitudes (Pacific and Indian Deep Waters; e.g., Talley 2013). Some recent examples of such analyses are reviewed in Talley et al. (2016). Using these transport estimates, the distribution of diapycnal mixing can be inferred.

The CTD profiles collected in GO-SHIP along with direct velocity profiles are being used to more directly estimate diapycnal diffusivity, using a parameterization of internal wave turbulence. These have demonstrated that diffusivity is bottom-intensified, most likely due to wave breaking over rough topography (Kunze et al. 2006; Huussen et al. 2012). Capturing this structure of deep mixing is essential for improvements in global climate models. Recently, temperature microstructure measurements have been taken on some GO-SHIP cruises, allowing even more direct estimates of diffusivity to be made.

The future of GO-SHIP

The past three-plus decades of repeat hydrography — observing physical, biogeochemical, and transient tracer distributions in the global ocean, as well as their variations — is the source of much that we know about the deep ocean circulation, water properties, uptake of anthropogenic carbon, and changes associated with climate. GO-SHIP is a major partner in the Global Ocean Observing System, providing the highly accurate reference measurements that are required for ongoing calibration and analysis of the growing fleet of autonomous profiling floats. All recent GO-SHIP cruises have served as delivery/calibration cruises for multiple types of profiling floats in the global Argo program, and stronger coordination is building between GO-SHIP and Argo through the WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology in-situ Observing Programmes (JCOMMOPS).

Argo has revolutionized observing of the physical properties of the upper ocean — with its global, year-round observations of temperature and salinity from the sea surface to 2000 m, as well as velocity at float parking levels. Even so, there are several pieces of information that GO-SHIP supplies that Argo does not. First, GO-SHIP collects highly accurate salinity data traceable to international standards that are used in quality control and calibration of data from the Argo float CTDs, which can drift out of calibration after leaving the manufacturer.

Second, GO-SHIP provides quasi-synoptic, full-depth, coast-to-coast sections that are necessary for estimating meridional transports, resolving the boundary currents that Argo does not. GO-SHIP observations through the full depth will be even more critical for the ongoing expansion of Argo to the deep ocean (Deep Argo; Zilberman and Roemmich this issue), where salinity measurement accuracy must be even higher than in the upper ocean because of its often-small variability.

GO-SHIP provides a very accurate high-quality, full-depth, and comprehensive set of ocean biogeochemistry data at a global scale, as well as transient tracer data that can only be measured from ships. However, a growing fleet of biogeochemical Argo floats (BGC-Argo), which, like Argo, provide much higher sampling in space and time, is highly complementary to GO-SHIP. Most BGC-Argo floats are equipped with oxygen and optical sensors that are increasingly stable, and a growing number have nutrient and carbon-related sensors (currently pH). Deep Argo, with its growing fleet, also includes oxygen sensors on some floats. However, all float sensors require *in situ* (GO-SHIP) reference data to obtain climate-quality accuracies. GO-SHIP measurements are required for not only for float instrument calibration but also to derive decadally evolving algorithms that connect the limited set of carbon cycle elements measured by the floats to the comprehensive set by GO-SHIP (e.g., Carter et al. 2016; Williams et al. 2017). The two observing systems will remain strongly linked well into the next several decades.

With increased societal interest in the health of ocean ecosystems, future GO-SHIP efforts will incorporate key parameters to address this aspect. This will also dovetail into BGC-Argo and satellite oceanography, where properties such as ocean color, fluorescence, and particulate matter need to be validated and translated to chlorophyll and planktonic species. A proposal was submitted to the Scientific Committee on Oceanic Research (SCOR) in April 2017 to form a working group on the "Integration of Plankton-Observing Sensor Systems to Existing Global Sampling Program" that will address details of augmenting GO-SHIP with key biological variables.

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