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Ship-based Repeat Hydrography: A Strategy for a Sustained Global Programme

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Ship-based Repeat Hydrography: A Strategy for a Sustained Global Programme

A Community White Paper developed by the Global Ocean Ship-based Repeat Hydrographic Investigations Panel for the OceanObs ’09 Conference, Venice, Italy, 21–25 September 2009

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Executive Summary

Ship-based hydrography is the only method for obtaining high-quality measurements with high spatial and vertical resolution of a suite of physical, chemical, and biological parameters over the full ocean water column, and in areas of the ocean inaccessible to other platforms. Global hydrographic surveys have been carried out approximately every decade since the 1970s through research programs such as GEOSECS, TTO/SAVE, WOCE / JGOFS, and CLIVAR. It is time to consider how future surveys can build on these foundations to create a coordinated network of sustained ship-based hydrographic sections that will become an integral component of the ocean observing system.

This white paper provides scientific justification and guidelines for the development of a regular and coordinated global survey. Two types of surveys are required to meet scientific objectives: (1) a global decadal survey conducted such that each full ocean basin is observed over an approximately synoptic time-period (< 3 years), and (2) a sub-set of the decadal survey lines sampled at high-frequency (repeats every 2-3 years). Given the end date of the present sampling programs, a coordinated global survey should begin before 2012 to maintain continuity.

While it is essential to maintain a repeat hydrography program firmly linked to national, regional and international research programs, some elements of coordination and implementation could benefit from a more pro-active oversight structure. These include the development of a sustained international coordination body for an interdisciplinary repeat hydrography program that is independent of any single time-limited research program (for example, following the model of Argo or OceanSITES); and a single, international information and communications forum to facilitate field program planning, to set experimental standards and methods, and to underpin data sharing / synthesis activities, including international data management activities.

Thirteen countries currently participate in the global repeat hydrographic program. The cost of repeat hydrographic sections currently implemented is estimated to be approximately US $10 Million dollars per year. New resources will be required for maintenance of lines, upgrading of the data assembly center network, joint synthesis activities, and international coordination activities.

Acknowledgments

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1. Introduction

Despite numerous technological advances over the last several decades, ship-based hydrography remains the only method for obtaining high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column.

Ship-based hydrography is essential for documenting ocean changes throughout the water column, especially for the deep ocean below 2 km (52% of global ocean volume not sampled by profiling floats). Hydrographic measurements are needed to

- reduce uncertainties in global freshwater, heat, and sea-level budgets,
- determine the distributions and controls of natural and anthropogenic carbon (both organic and inorganic),
- determine ocean ventilation and circulation pathways and rates using chemical tracers,
- determine the variability and controls in water mass properties and ventilation,
- determine the significance of a wide range of biogeochemically and ecologically important properties in the ocean interior, and
- augment the historical database of full water column observations necessary for the study of long timescale changes.

These results will be critical for evaluating ocean models and providing data constraints for state estimation, assimilation and inverse models. In addition, ship-based hydrographic measurements provide a standard for validating new autonomous sensors and a reference/calibration dataset for other observing system elements (in particular Argo profiling floats, expendable bathythermographs and gliders). Hydrography cruises also provide cost-effective access to remote ocean areas for the deployment of these instruments.

The first attempt at a global hydrographic survey took place during the International Geophysical Year (1957-1958), but only in the Atlantic was a systematic high-quality survey conducted (King et al., 2001). The Geochemical Ocean Sections Study (GEOSECS) did provide hydrographic surveys in all three major ocean basins (Atlantic 1972-73, Pacific 1973-74, and Indian 1977-78), but focused on the chemistry and did not provide high-resolution land-to-land transects. It was not until the decade of the 1990s that the World Ocean Circulation Experiment (WOCE) conducted an extensive survey of hydrographic properties and circulation in the global ocean in an effort to develop a global picture of ocean transport that was as synoptic as possible. In collaboration with the WOCE global survey, the Joint Global Ocean Flux Study (JGOFS) ensured that carbon measurements were made on a majority of the cruises. The WOCE/JGOFS effort led to numerous scientific advances in understanding the physical and biogeochemical state of the global ocean, including

- computation of a globally consistent picture of meridional heat, freshwater, oxygen and nutrient transport (Ganachaud 2003a; Ganachaud and Wunsch, 2002, 2003) with associated estimates of divergence and air-sea exchange, and a comprehensive analysis of the errors involved (Ganachaud, 2003b),
- quantification of the temporal variations of oxygen from biology, ventilation, and circulation (Deutsch et al., 2005; Deutsch et al., 2006),
- characterization from the spatial patterns of alkalinity of the production and dissolution of calcium carbonate (Sarmiento et al., 2002) and the impact of anthropogenic CO2 on ocean acidification (Feely et al., 2004; Orr et al., 2005)
- determination of the global-scale inventory of anthropogenic CO_2 in the ocean (Sabine et al., 2004), which is providing unprecedented constraints on the global re-distribution of anthropogenic CO_2 (see e.g.IPCC, 2007),

- development of constraints on ocean centennial and decadal time-scale ventilation from natural and bomb-radiocarbon (Matsumoto et al., 2004), and documentation of ventilation pathways returning deep-water to the upper ocean using ^{3}He (Dutay et al., 2004),
- estimation of oceanic denitrification and nitrogen fixation rates (Gruber and Sarmiento, 1997; Howell et al., 1997; Deutsch et al., 2001),
- construction of the first large-scale data set of full-depth diapycnal diffusivities covering all major ocean basins (Kunze et al., 2006),
- development and application of inverse methods that estimate the exchange fluxes of natural and anthropogenic carbon between the atmosphere and the ocean (Mikaloff-Fletcher et al., 2006, 2007),
- development of assimilating basin and global-scale models bringing insight to our understanding of 3-dimensional time-varying ocean circulation and its impact on property budgets and their variability (Mazloff 2008; Douglass et al., 2008; Baehr et al., 2008; Wunsch and Heimbach, 2006; Stammer et al., 2002),
- determination of regional (e. g. Orsi et al. 1999) and global-scale oceanic inventories (e. g. Willey et al., 2004) and distribution of CFCs, which has provided a means to determine water-mass formation rates and the oceanic uptake of anthropogenic CO_2 (e.g. McNeil et al., 2003; Waugh et al., 2006), and
- the first accurate estimates of dissolved organic carbon (DOC) in the ocean and its transport (Hansell and Carlson, 2001; Hansell et al., 2004).

While WOCE and JGOFS were successful in answering many first-order questions about large-scale ocean circulation and carbon inventories, their results also raised many new questions concerning ocean variability, controls on carbon and tracer inventories and distributions and long-term secular trends associated with climate change, oceanic CO_2 uptake and ocean acidification. These programs confirmed that the ocean exhibits significant interannual variability on top of the expected smooth decadal trend as part of patterns of global change, complicating efforts to detect and attribute human influences on the ocean. WOCE and JGOFS, along with many other studies conducted over the last two decades, suggests that the effect of climate forcing on the ocean may be substantial, but is poorly understood, and that the next generation of hydrographic surveys would need to be designed to examine the drivers and impacts of this variability, in concert with modelling and assimilation activities.

An international conference entitled “The Ocean Observing System for Climate” (or OceanObs’99) set the initial scientific and implementation framework for post-WOCE hydrography (see, e.g., Fine et al., 1999). Recognizing the need to focus research on climate variability as well as on the documentation of trends from anthropogenic forcing, it was decided to incorporate a program of repeat hydrography in the 15-year international Climate Variability and Predictability Study (CLIVAR). This first global repeat survey of a select subset of WOCE hydrographic sections is scheduled to be completed in 2012 and the field program is presently 75% completed.

Preliminary results show significant changes in water mass distributions and biogeochemical properties over the last decade, influenced by both secular changes (e.g., anthropogenic CO_2 invasion) and natural climate mode variability such as the North Atlantic Oscillation, the Pacific Decadal Oscillation and the Southern Annular Mode. Some recent research highlights on interannual variability include

- documentation of substantial changes in the oceanic inorganic carbon content, driven by both the uptake of anthropogenic CO_2 and natural variability
- evidence of large-scale changes in oceanic oxygen concentrations
- near global-scale warming of abyssal waters of Antarctic origin, and freshening of these waters in deep basins adjacent to Antarctica
- freshening of the Atlantic waters
- equatorward penetration of CFCs from high-latitude sources filling the deep and abyssal basins on time scales of decades, allowing estimates of water mass formation rates, and

- evidence of reduction in downstream primary productivity brought on by strong convection and mode water formation.

These results illustrate the importance of repeated global surveys for interpreting and attributing changes to physical and dynamical mechanisms operating on a variety of time scales. As this CLIVAR hydrography program comes to an end, it is clear that the global repeat survey approach is very effective at quantifying variability and trends of a large suite of physical and biogeochemical parameters. Integration of ship-based repeat hydrography with other observing system elements, such as the Argo profiling float program, Ship of Opportunity Program, Volunteer Observing Ship Program, time-series stations and satellite remote sensing that provide complementary scales of information, is required for the accurate monitoring of ocean change and variability. A comprehensive ocean observing system, in conjunction with synthesis and numerical models, is vital to understand the drivers of global climate change and variability

It is time to consider how future global ship-based hydrography can build on the foundations established by the global surveys of GEOSECS, WOCE, JGOFS, and CLIVAR. The IOCCP and CLIVAR, in collaboration with the Integrated Marine Biogeochemistry and Ecosystem Research Project (IMBER) and the Surface Ocean-Lower Atmosphere Study (SOLAS), developed the Global Ocean Ship-based Hydrographic Investigations Panel (GO-SHIP) to bring together interests from physical hydrography, carbon, biogeochemistry, Argo, OceanSITES, and other users and collectors of survey data. The Panel is tasked to develop guidelines and a general strategy for the development of a globally coordinated network of sustained ship-based hydrographic sections that will become an integral component of the ocean observing system.

While it is essential to maintain a repeat hydrography program firmly linked to national, regional and global research programs, some elements of coordination and implementation could benefit from a more proactive oversight structure, including the development of

- a sustained international coordination body and scientific steering committee for integrated/interdisciplinary repeat hydrography that is independent of any specific time-limited research program (for example, following the model of Argo or OceanSITES)
- a single, international information and communications forum to facilitate field program planning, agreements on standards and methods, and data sharing/synthesis activities, and
- coordinated international data management and data synthesis activities.

The following sections outline the scientific objectives and rationale for a repeat ship-based hydrographic program (Section 2), the temporal and spatial sampling strategy to achieve those objectives (Section 3), and the recommended data management, data sharing and product development (Section 4).

2. Scientific Objectives and Rationale

The principal scientific objectives for a sustained repeat ship-based hydrography program have two closely linked components: (1) understanding and documenting the large-scale ocean water property distributions, their changes, and drivers of those changes, and (2) addressing questions of a future ocean that will increase in dissolved inorganic carbon (DIC), become more acidic and more stratified, and experience changes in circulation and ventilation processes due to global warming, altered water cycle and sea-ice. An observation program must be designed in light of these expected changes (and potential surprises) and the way in which they will interact with natural ocean variability.

2.1 Understanding the controls and distribution of natural and anthropogenic carbon and biogeochemistry in the ocean interior

Inorganic carbon and anthropogenic carbon

Recent results from the repeat hydrography cruises show that anthropogenic CO_2 is continuing to accumulate in the Atlantic, Pacific, and Indian oceans (e.g. Tanhua et al., 2006, 2007; Sabine et al., 2008; Murata et al., 2007, 2008). Thus far the anthropogenic CO_2 accumulations generally agree with the estimated long-term storage patterns of Sabine et al. (2004) with the largest inventories associated with regions where water masses are being formed and moving into the ocean interior. However, the repeat hydrography sections completed so far have shown that there are important regional differences in total carbon storage and the global repeat survey is not yet finished. Results in both the Pacific and Atlantic oceans have shown that circulation changes can have a significant impact on the net total change in carbon inventory on decadal time scales. In some cases these changes may enhance the regional storage of carbon and in other cases they may decrease the uptake resulting from rising atmospheric CO_2. In the Northwestern Atlantic, the reduction of deep water formation led to a decrease of the inventory of anthropogenic carbon by 9% over the period from 1997 to 2003 (Steinfeldt et al., 2009). Using measured changes in the $^{13}C/^{12}C$ of DIC in the North Atlantic between 1993 and 2003, Quay et al. (2007) estimated that about half of the anthropogenic CO_2 accumulation in the North Atlantic was the result of northward advection of surface waters. The effect of varying circulation on the total DIC change is estimated to be greater than 10 $\mu mol\ kg^{-1}$ in the North Pacific, accounting for as much as 80% of the total DIC change in that region (Sabine et al., 2008).

It is not clear from repeat hydrography measurements alone whether these dynamic variations reflect processes acting on seasonal, interannual, or decadal time scales (Doney et al., 2009a). The potential importance of relatively high-frequency dynamic variations is in full evidence in the tropical Indian Ocean, where seasonal variations in the thermocline circulation can drive changes in the natural carbon inventories of 10 moles C m^{-2} over 6 months (Rodgers et al., 2009). As additional cruises are completed the full picture of the decadal storage will be developed.

Emerging issues and implications for sampling: Improved understanding of the decadal scale variations in CO_2 accumulation requires continuation of global decadal repeat- hydrography, and additionally, frequent repeats in active areas, such as the North Atlantic, Southern and North Pacific oceans, with sub-annual sampling in some regions to better distinguish between anthropogenic and natural CO_2 variability (Levine et al., 2008; Perez et al., 2008). Because circulation and biological changes can vary in response to local or regional climate forcing on time scales that are not yet fully understood, it is critical to continue to monitor the changes in carbon inventories and how they interact with the long-term increases in anthropogenic CO_2 and climate. Monitoring this variability and attributing changes to drivers requires a simultaneous suite of observations of physical parameters, nutrients, O_2, carbon, multiple tracers, and isotopes. If we are to understand the migration of anthropogenic CO_2 from the atmosphere into the ocean, radiocarbon and other tracers such as ^{13}C, tritium - ^{3}He, and CFCs are critical measurements and should be core variables of the next decade of hydrography (*see also Section 2.3 for a discussion of tracers*).

Of all the transient tracers commonly used for oceanographic investigation, radiocarbon has the longest measurement history, dating back to the late 1940s. Data from the 1940s and 1950s are not as accurate as modern measurements; however, they are adequate for many applications. Since GEOSECS in the 1970s radiocarbon has routinely been measured to $4^{o}/_{oo}$ or better. During the 1960s the natural or background ocean (and atmosphere) radiocarbon concentrations were strongly influenced by atmospheric testing of nuclear weapons. Due mostly to ocean uptake, the atmospheric radiocarbon concentration history resembles an extremely strong spike with an exponentially decaying tail which has leveled off in recent years as it nears background levels. In the years since the 1970s, by re-measuring the thermocline radiocarbon distribution, we have been able to document the spike movement through those waters. Since the bomb spike was so large, following the changes in the thermocline are easy and unambiguous with modern analysis methods.

Figure 1 below shows three approximately decadal "change sections" for P16 in the eastern Pacific. In addition to thermocline ventilation issues, the natural radiocarbon distribution in the deep and intermediate waters has been and continues to be one of the more valuable measurements for the determination of ventilation rates in deep and abyssal waters. Integration of the oceanic bomb component (Key et al., 2004, Peacock, 2004), using the relatively complete WOCE data provided the most accurate estimates of global air-sea gas exchange rates for CO_2 (Sweeney et al., 2007).

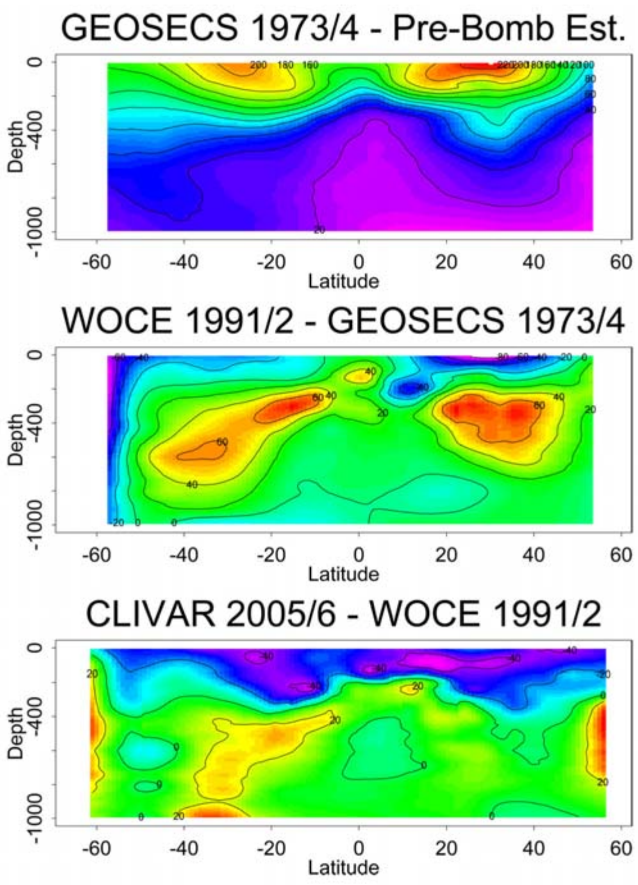

Figure 1. $\Delta^{14}C$ change in $^{o}/_{oo}$ over three hydrographic programs spanning approximately 3 decades on line P16 in the eastern Pacific. Change is calculated as a simple difference, with red indicating an increase and blue a decrease. Pre-bomb values were estimated using the potential alkalinity method of Rubin and Key (2002). Anything larger than 6 $^{o}/_{oo}$ is significant. (*Robert Key, Princeton University, unpublished data*.)

The $^{13}C/^{12}C$ of DIC is also a well-used tracer of the ocean's carbon cycle in both the modern and paleo-ocean. One important application with climatic importance is the use of $^{13}C/^{12}C$ to track the accumulation of anthropogenic CO_2 in the ocean (e.g., Quay et al., 2003). This application is based on the observation that the $^{13}C/^{12}C$ of CO_2 produced by fossil fuel combustion is substantially lower (by ~20 $^{o}/_{oo}$) than the $^{13}C/^{12}C$ of atmospheric CO_2. As a result, when anthropogenic CO_2 is absorbed by the ocean, the $^{13}C/^{12}C$ of the ocean DIC decreases. Therefore, by measuring the rate of the $^{13}C/^{12}C$ decrease, one can estimate the rate of anthropogenic CO_2 build-up in the ocean. One advantage of using $^{13}C/^{12}C$ to track the build-up of anthropogenic CO_2 in the ocean is its higher signal-to- noise ratio than for the DIC change itself. Continued measurements of the decadal change in the $^{13}C/^{12}C$ of DIC in the ocean will provide estimates of oceanic CO_2 uptake rates that complement rates estimated from measuring the ocean DIC change.

Dissolved organic carbon and export flux

The ocean pool of dissolved organic matter contains 662 Pg carbon (Hansell et al., submitted), an inventory similar in magnitude to that of CO_2 in the atmosphere. Small perturbations in the source/sink mechanisms of dissolved organic carbon (DOC) could impact the exchange of carbon between the ocean and atmosphere. Prior to the DOC surveys conducted as part of the CLIVAR Repeat Hydrography program, our knowledge of DOC biogeochemistry on the global scale was limited to a few high-precision measurements scattered widely across ocean basins (Hansell and Carlson, 1998; Hansell, 2002). The recent surveys have resulted in unprecedented resolution and insights on the distribution and dynamics of DOC. Highly resolved DOC concentration gradients in the deep ocean trace the flow of the thermohaline circulation, allowing characterization of the deep water masses by their DOC signatures. DOC removal rates in the deep ocean are very slow (Carlson et al., *in press*), as evidenced by removal in the Pacific at a few nmol kg^{-1} y^{-1} (Hansell et al., submitted). This low rate of removal is thought to be due to the low bioavailability of the residual dissolved organic matter, but it now appears that the low deep ocean temperatures serve to restrict biological mineralization of DOC as well (Carlson et al., *in press*). An eventual warming of the deep sea may result in accelerated removal of the most biologically recalcitrant DOC.

Emerging Issues and implications for sampling: DOC export represents a significant component of the biological pump in regions that undergo deep convective mixing (Copin-Montégut and Avril, 1993, Carlson et al., 1994) or ventilation of intermediate waters (Hansell et al. 2002). DOC undergoes net export to depths greater than 100 m at approx. 1.8 Pg C yr-1, or 20% of global export production from sinking particles (Hansell, 2002). Of particular interest is how a change in ocean stratification will affect the role of DOC in the biological pump. Will DOC export become more or less important relative to particulate organic carbon (POC) export as ocean stratification changes? Will changes in ocean stratification affect the inventory of carbon sequestered in the dissolved organic phase and what will be the direction and magnitude of such a change? With the first-ever global ocean survey of DOC in progress, the community is poised to examine decadal variability of the dissolved organic as well as the inorganic carbon pools within the oceanic water column. The key questions described above can only truly be addressed with continued repeat hydrographic sections.

Ocean acidification

Ocean acidification is another impact of increasing CO_2 in the atmosphere, and is also a topic for which global surveys are urgently needed. CO_2 is a weak acid, and reacts with seawater to form carbonic acid (H_2CO_3) when it dissolves in the ocean. H_2CO_3 dissociates to form a hydrogen ion (H^+) and a bi-carbonate ion (HCO_3^-). Some H^+ ions react with carbonate ions (CO_3^{2-}) to produce more HCO_3^- ions. From this series of reactions, CO_2 uptake by the ocean causes increases in H^+ (decreases in pH) and decreases in CO_3^{2-}. These changes impact a large range of biogeochemical and ecological processes in the ocean (Doney et al., 2009b). One of the impacts is a decrease of saturation state of calcium carbonate ($CaCO_3$), which is unfavorable for $CaCO_3$-secreting species. Decreases of the saturation state are already reported in open ocean (Feely et al., 2002; Sabine et al., 2002; Sarma et al., 2002).

Emerging issues and implications for sampling: Spatial and temporal variability of the calcium carbonate saturation state is related not only to CO_2 storage in the ocean interior, but also to ocean circulation, temperature and biology (Feely et al., 2004). Thus basin-scale coverage by repeat hydrography and the ocean carbon observing network for ocean acidification will provide the required information to determine the chemical changes that are occurring in the oceans and to model their ecological impacts (e.g., see OceanObs09 Community White Paper by Feely et al.).

Nutrients

Nutrient observations, important in their own right because of their relation to biogeochemical cycles, can be used as a vital component of circulation estimation (Robbins and Toole, 1997), and are also used in some anthropogenic carbon derivations as well as multi-parameter regressions of less well sampled properties (e.g. Holfort et al., 1998; Gruber et al., 1996).

In the North Pacific Ocean along 24˚N, slight increases in silicate concentration were observed around the density of the central mode water where apparent oxygen utilization increased by up to 6 μmol kg^{-1} from 1985 to 2005 (Kouketsu et al., 2009). In the entire Pacific Ocean, the rate of change in silicate concentration has varied by ± 0.4 μmol kg^{-1} y^{-1} from the 1990s to 2000s based on a analysis of 7 WOCE/CLIVAR cruises within the areas of LCDW pathway (Aoyama et al., 2009) which is consistent with recently reported warming of a few mK in the deep waters in the North Pacific Ocean (Fukasawa et al., 2004; Kawano et al., 2006). It is clear from intercomparison exercises between laboratories (e.g. Aoyama et al., 2009) that there are large biases in reported nutrient values. This is also confirmed in comparisons of deep water samples between oceanographic cruises, where large biases in the reported values are found (e.g. Johnson et al., 2001; Gouretski and Jancke, 2001). The size of the biases in nutrient concentration are of the same magnitude as, or often significantly larger than, temporal changes in concentrations or ratios between nutrients, making the detection of trends extremely difficult. For instance, Pahlow and Riebesell (2000) found increasing N:P ratios in the North Atlantic possibly indicating shifts in the Redfield ratios, a result that might be compromised by systematic biases in the nutrient data (Zhang et al., 2000).

Emerging issues and implications for sampling: The comparability and traceability of nutrient data in the global oceans are fundamental issues in marine science, and particularly for studies of global change. However, as pointed out in the IPCC 4th Assessment Report, large regional changes in nutrient ratios have been observed with no consistent patterns, which may be the result of systematic analytical offsets over time or between laboratories for deep ocean nutrient observations. Nutrient values tend to be high in old waters, where the anthropogenic carbon signal is small. Therefore, even a relatively small bias in nutrient data can bias the estimated anthropogenic carbon significantly in a region where the anthropogenic carbon concentration is normally low. Even if the absolute difference in anthropogenic carbon is small, there is a large volume of low anthropogenic carbon/high nutrient waters in the world oceans. Thus, biased nutrient data will make a noticeable difference to the carbon inventory calculations obtained from methods that rely on nutrient data. The international community is working to develop certified reference materials and protocols for high-quality nutrient measurements. This effort is essential for resolving discrepancies in open ocean nutrient changes as well as reducing the uncertainty in estimates of anthropogenic CO_2 uptake. For any future hydrographic survey, the use of nutrient reference materials should be mandatory, even if the standards are not yet perfect. Both the Global Ocean Data Analysis Project (GLODAP) and the Carbon in the Atlantic Program (CARINA) have made this point clear.

Oxygen

As a consequence of increased stratification due to global warming and changes in ocean biology due to warming, increased CO_2 concentration and decreased pH, climate and biogeochemical models predict a decline in oceanic oxygen concentrations (e.g. Bopp et al., 2002; Oeschlies et al., 2008). These changes have important direct implications for biology, and trigger feedback mechanisms on nutrient (nitrate) and carbon cycling, such as increased extent of oxygen minimum zones, increased de-nitrification, and possibly reduced export production in the photic zone. However, a series of complex feedback loops are at work, including changes in circulation and nitrogen fixation. Oxygen changes observed from repeat hydrography have shown the extent of variability in upper ocean biogeochemistry, including decreases in ocean oxygen content associated with mode and intermediate waters in the mid and high latitudes of the Pacific (Emerson et al. 2004, Sabine et al 2008); North Atlantic (Johnson and Gruber, 2007, Garcia et al., 1998), and South Indian oceans (Bindoff and McDougal, 2000); and even lower concentrations of oxygen in, and larger extent of, oxygen minimum zones (Stramma et al., 2008). However, decadal sampling does not provide sufficient information about the full temporal and spatial scope of oxygen changes and their drivers. Addition of O_2 sensors on Argo floats is being tested to address this problem. Changes in the ocean oxygen inventory will also affect estimates of the land-ocean anthropogenic CO_2 partitioning that are based on observations of relative changes of the O_2 and CO_2 concentrations in the atmosphere (Keeling and Garcia, 2002).

Emerging issues and implications for sampling: Even though the upper ocean oxygen content can, in principle, be monitored by Argo floats equipped with oxygen sensors, potential drift and bias of these sensors should be monitored by comparison with ship based observations. Further, the only currently available method for monitoring changes in oxygen over large areas of the deep ocean is via ship-based repeat hydrography with high-quality oxygen measurements. Careful monitoring of changes in oxygen concentrations will allow for evaluation of oxygen sensitive tipping points, with possible wide-spread consequences for fisheries and ecosystems.

Pigments and bio-optical measurements

Bio-optical data obtained through repeat hydrography can provide information on the distribution of various phytoplankton types on a global scale. Such information is essential to evaluate how different phytoplankton types respond to a change in climate, or to changes in the environment, such as ocean acidification. The information would also be useful in models designed to study associated impacts on elemental cycles. Satellite ocean-colour data provide a wealth of information on phytoplankton concentrations and distributions, but globally distributed data for ground-truth are essential to complement this information. The data from repeat hydrography can be used to test and calibrate satellite ocean-colour measurements from different sensors, and the development and improvement of regional algorithms for satellite-derived estimates of phytoplankton biomass and primary production. Ocean-colour data is also used to estimate particulate organic carbon, particulate inorganic carbon, and chlorophyll-a concentration, which are linked to carbon cycling, both in the ocean interior and between the surface ocean and atmosphere.

To quantify the underwater light environment and to obtain better estimates of phytoplankton standing stocks and production (and thus carbon flux), it is desirable to measure a comprehensive suite of bio-optical parameters, including pigment concentrations, on future hydrographic cruises. The 2003 JAMSTEC Blue EArth Global Expedition (BEAGLE) circumpolar cruise in the Southern Hemisphere revealed unexpected features in the distribution of Prochlorococcus ecotypes. Repeat hydrography is an essential platform for these observations because global repeat coverage is required to understand the global distribution patterns of phytoplankton species and their variations with time. Many areas of the global ocean are completely unsampled; where measurements do exist, there are not many seasonal comparisons.

Emerging issues and implications for sampling: Ideally, POC, phytoplankton pigments and absorption, and number and size of phytoplankton and other microbial cells by flow cytometry should be measured at all sampling stations as a vertical profile down to the 1% light level. Photosynthetic available radiation (PAR) measurements should be included on rosette systems with Niskin-type sampler bottles coupled with a conductivity-temperature-depth sensor package (i.e, CTD/rosette) where practicable, and irradiance should be measured at specific wavelengths. Fluorometers are currently pressure-rated down to 6,000 m; however, technological advances are required to develop other sensors (e.g. PAR sensors) that are pressure-rated for deep casts. Repeating the hydrographic cruises in different seasons would also be highly desirable.

Trace elements and isotopes

The limited availability of the micronutrient iron (Fe) in the upper waters of the ocean is a key control on biological production in several remote high nutrient - low chlorophyll (HNLC) ocean regions, due to the limited supply of Fe-containing atmospheric dust to the surface waters in these regions. Thus, successful models of the biological pump need to accurately reproduce the distribution of dissolved Fe in surface waters and its supply to the open ocean from the partial dissolution of continental mineral dust. The importance of the transport and partial dissolution of continental mineral dust as a major source of dissolved iron to surface waters is now well established (see review by Jickells et al., 2005). The importance of understanding and quantifying this process is underscored by the coincidence of HNLC regions of the ocean with regions that are believed to receive extremely low amounts of aerosol deposition. The importance of understanding atmospheric dust fluxes is further strengthened by the large increases in the transport of aeolian material recorded in sediments and ice cores during glacial maxima (De Angelis et al., 1987; Kumar et al., 1995; Laj et al., 1997). The presumed enhanced flux of Fe to surface waters during these periods and the consequent effect on surface productivity provide a potential link between orbitally induced climatic variations and the lower atmospheric CO_2 levels observed during these periods. Recent work has suggested that human-produced aerosols exhibit higher fractional Fe solubility than mineral dust, and that this component of the atmospheric aerosol load is sure to increase with global population growth (Sedwick et al., 2007).

Until recently, the time-intensive sampling methodology required to obtain water samples for trace element determinations free of contamination artifacts had precluded the inclusion of this kind of sampling as part of large-scale hydrography programs. Development of a trace element-clean sampling rosette system for the CLIVAR repeat hydrography program (Measures et al., 2008a) has allowed a parallel sampling program to be conducted over the last 6 years in the upper 1,000m as part of the CLIVAR program. High-resolution sampling along the CLIVAR hydrography cruise tracks is providing a first-order data set of the availability of the micronutrient Fe and the aerosol deposition tracer, Aluminum, which will be used as ground-truth for these models. Initial results indicate that high-resolution sampling is identifying previously unrecognized regions of preferential atmospheric deposition as well as a close connection between the deposition patterns and Fe availability (Measures et al., 2008b).

Methods for shipboard collection of aerosol and rainfall samples are now well established (Baker et al., 2006a,b; Buck et al., 2006). These samples can be analyzed for soluble and residual Fe and a large suite of biogeochemically important trace elements and isotopes. These data can then be used to constrain and calibrate dust transport and deposition models, in particular for trace elements and isotopes such as dissolved Al and Manganese (Mn), which both serve as tracers of atmospheric deposition, and for dissolved Fe, which has significant implications for biological productivity and carbon fluxes from the photic zone. The aerosol and rainfall sampling systems are deployed forward of the bridge on all ships, and do not interfere with the normal hydrographic operations. They typically require one person to operate the equipment and collect and process the samples that are collected on a daily (24-hour) basis.

Emerging issues and implications for sampling: The demonstration of the feasibility of these sampling approaches and results they have obtained have been instrumental in developing a new geochemically driven sampling program GEOTRACES. This multi-PI, international program aims to build a framework of understanding about the distribution of a large number of important trace elements and isotopes (TEI) that can be used to identify sources and quantify fluxes of these materials throughout the ocean. The GEOTRACES program seeks this information throughout the water column and utilizes the interpretative power of multiple TEIs to constrain our understanding of contemporary processes to build a framework that will enable a detailed interpretation of the paleoceanographic record. The sampling volumes required to characterize multiple TEI and the number of personnel required to make specialized shipboard determinations requires a stand-alone program, with cruise tracks attuned to biogeochemical rather than zonal and meridional gradients. However, the adoption by GEOTRACES of the same high-quality hydrographic protocols used by repeat hydrography will ensure a synergy between the programs and ensure that the data sets produced can provide information in regions not visited by repeat hydrography programs. While characterizing the core TEI of the GEOTRACES program does not require the spatial or temporal resolution of the hydrography programs, certain subset parameters would benefit from inclusion in future high-frequency repeat sections. In particular, this is likely for parameters that can be used to deduce atmospheric mineral dust deposition to the surface ocean. Not only are these deposition processes highly variable temporally and spatially in the contemporary ocean, they are also likely to vary with climatically induced changes in rainfall patterns, leading to variations in the delivery of micronutrients to important regions of the open ocean.

2.2 Understanding ocean changes below 2 kilometers and their contributions to global heat budget and sea-level budgets

The global network of Argo profiling floats samples the physical characteristics of the upper 2 km of the global ocean, half the global ocean volume. Ship-based repeat hydrographic sections are an essential, and in most regions the only, observing element for the study of changes in deep and bottom water formation rates and properties, their signatures as they spread out from formation regions, and for providing detailed basin-scale points of comparison for global circulation models. Sections occupied during CLIVAR, when compared to those taken during WOCE, reveal substantial variability in many regions, and subtle but measurable variability in others. For instance, a section repeated yearly across the Labrador Sea provides a rich data set for analyses of variations in the components of North Atlantic Deep Water, such as the Labrador Sea Water, the Iceland-Scotland Overflow Water, and the Denmark Straits Overflow Water (e.g. Yashayaev, 2007). Repeat sections show how these signals spread throughout the North Atlantic. Decadal variations in Labrador Sea Water properties can be traced to 20°W in an analysis of data from the CLIVAR/CO_2 reoccupation of WHP Section A16N in 2003 along with three previous occupations (Johnson et al., 2005). North Atlantic Deep Water property variations have been traced to 24°N in an analysis of repeat section data along this section (Cunningham and Alderson, 2007) and have also been traced southward to 16°N (Steinfeldt et al., 2007).

However, deep variability evident in repeat hydrographic sections is not by any means limited to the North Atlantic Deep Water. Warming abyssal ocean temperatures linked to Antarctic Bottom Water sources appear to be widespread in the Atlantic, Indian, and Pacific oceans. Deep and bottom warming has been detected over the past several decades in the Weddell Sea (Robertson et al., 2002; Fahrbach et al., 2004). Downstream of this region, statistically significant warming has been detected in the bottom waters of the all western basins of the South Atlantic Ocean (Figure 2, Johnson and Doney, 2006) and warming signals appear to extend into the abyssal western North Atlantic (Johnson et al., 2008b). This warming is apparent throughout the Pacific Ocean (Kawano et al., 2006; Johnson et al. 2007), even to the rather surprising location of 47°N in the Pacific Ocean (Fukasawa et al. 2004).

Freshening of these bottom waters is apparent closer to their source, such as the Australian-Antarctic Basin (Rintoul, 2007; Johnson et al., 2008a). This freshening may be linked to freshening in the source regions such as the Adelie Land and the Ross Sea (Jacobs et al., 2002). The freshening observed in this basin, combined with the warming approaching 0.1°C over 12 years, accounts for about 5 cm of steric sea level rise below 2 km (Johnson et al. 2008a). Finally, in addition to suggesting global changes in the thermohaline circulation, the warming (and freshening) observed in the abyss could play a non-trivial role in global heat budgets and sea level rise (Johnson et al., 2007; 2008a).

Emerging issues and implications for sampling: The abyssal freshening near Antarctica and near global abyssal warming observed in recent decades, as well as water property variability in the North Atlantic limb of the meridional overturning circulation, demonstrate a requirement for future global sampling of the ocean below the current 2 km depth limit of Argo. What is the ongoing contribution of the abyssal ocean to the global heat and freshwater budgets? Will the heat and freshwater apparently being sequestered in the abyssal regions ventilated from Antarctica continue to build, or will the recent changes reverse? How will changes in the properties of North Atlantic Deep Water propagate throughout the rest of the ocean? The continued repeat hydrographic sections proposed here will provide a very accurate, high-quality observational backbone for answering these and other questions, likely augmented by complementary arrays of moored instruments, and perhaps deeper profiling floats.

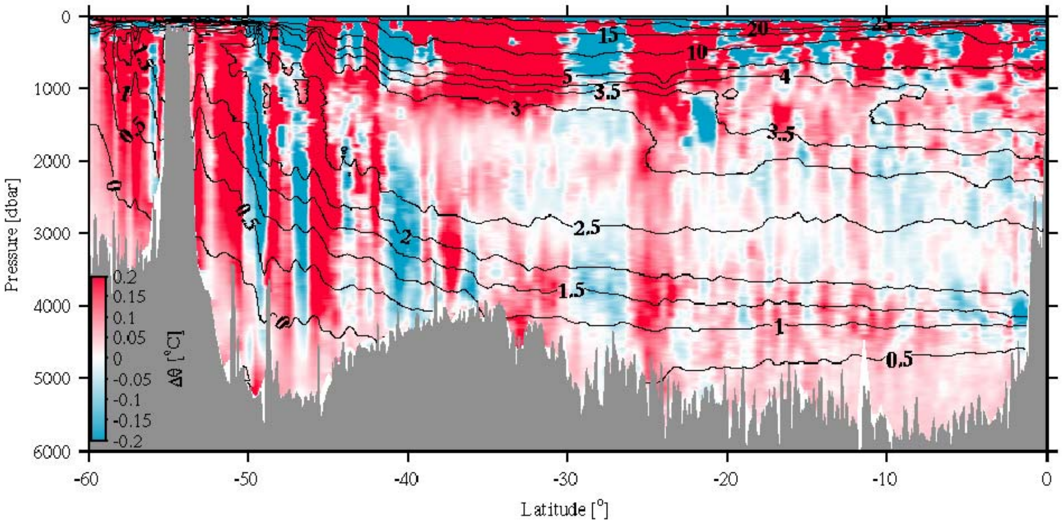

Figure 2. Potential temperature differences (red warm, blue cold) of the 2005 – 1989 occupations of A16S meridional section sampling the western basins of the South Atlantic. Mean isotherms from the two cruises are contoured (black lines) at 0.5°C intervals below 5°C, and 5°C intervals above. Note the warming of cold waters throughout the Scotia Sea (south of 53°S), and the warming of bottom waters deeper than about 3500 dbar throughout the Argentine and Brazil Basins to the north. Figure follows Johnson and Doney (2006).

2.3 Understanding the variability in water masses, ventilation, and pathways

Substantial variability in temperature, salinity, oxygen concentration and apparent oxygen utilization (AOU) has been detected in many regions of the ocean by comparing CLIVAR repeat sections with those of WOCE and older sections (Rintoul and England, 2002, Bryden et al. 2003, Emerson et al., 2004; Feely et. al., 2005; Garcia et al., 2005; McDonagh, et al., 2005; Boyer et al., 2007; Johnson and Gruber, 2007; Talley, 2008). These changes are amplified in the upper ocean (0-1500m) and in regions of local water mass formation.

In the North Atlantic, the water mass property variability is observed in several tracers and found throughout the water column. The water mass property changes appear to be related to variations in air-sea forcing, the North Atlantic Oscillation (NAO), the advective time scales for the subpolar and subtropical gyres and the deep western boundary currents. Reoccupation of WOCE sections as part of the CLIVAR/CO_2 surveys has demonstrated the relatively rapid equatorward progression of CFCs from high- latitude sources into the deep and abyssal waters of the world's oceans. Figure 2, below, shows a cross-section of the Deep Western Boundary Current at the northern and southern extremes. There are relatively high concentrations of CFC-11 in two cores coincident with Upper NADW and Lower NADW. UNADW consists of Upper and classical Labrador Sea Water. The largest concentration increases are associated with UNADW and observed in the offshore Gulf Stream recirculation (35-40°N).

The CFC concentrations have been used to estimate rates of formation for many water masses. Orsi et al. (1999) inferred a formation rate for AABW of 8 Sv. Smethie and Fine (2001) estimated NADW components, and LeBel et al. (2008) estimated the North Atlantic Meridional Overturning Circulation of 19.6 ± 4 Sv for the period 1970-97. In addition, using data from the subpolar region, Kieke et al. (2006) estimate formation rates for ULSW and LSW for the period 1997-2003. They find temporal switching between ULSW and CLSW in terms of strength of formation rates (for review of LSW formation rates see Haine et al., 2008). Using a variety of nutrients and tracers including SF_6, Tanhua et al. (2008) conclude that there is also temporal switching in percentage of LNADW component at the Denmark Strait sill between 1997 and 2002.

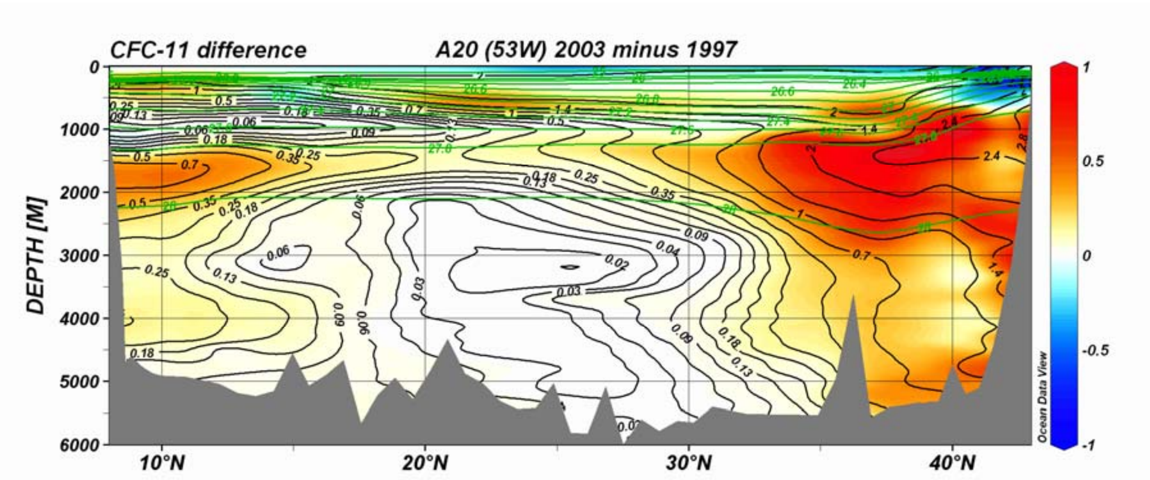

Figure 3. Black contours of CFC-11 in pmol/kg along A20 (53W) in 2003, with neutral density contours added in green. Superimposed are color contours showing differences in CFC-11 concentrations between the 2003 and 1997 occupation of the section (figure courtesy of Fine and Smethie).

In the North Pacific, property variability has also been linked to changes in gyre circulation and water mass ventilation rates in the formation regions. Repeat measurements of transient tracers in the North Pacific have been used to improve estimates of mixing in models (Sonnerup et al., 2008), and indicate a reduction of ventilation in the North Pacific subpolar gyre (Mecking et al., 2006).

The recent completions of the southern hemisphere CLIVAR sections are now also revealing interesting trends in upper-ocean properties in the south Pacific, Indian and Southern oceans (Talley et. al., 2008). In the Southern Hemisphere, subtropical basin property changes in the upper 1000m of the water column appear to be related to the Southern Annular Mode (SAM) variability and the southward trend of the westerly winds maximum (Roemmich et al., 2007). The large-scale atmospheric variability impacts the circulation of all the southern hemisphere subtropical gyres and the water mass formation regions north of the Antarctic Circumpolar Current and subtropical gyres. CFC concentration along a section in the Indian Ocean from the equator to Antarctica shows increasing CFC concentrations towards the bottom and southward in the abyssal basins south of the South Indian Ridge (45°S). The distribution of the CFC-12 concentration maxima broadly mirrors the observed abyssal warming and freshening found in the Southern Ocean abyssal basins.

Emerging issues and implications for sampling: The contemporaneous sampling of a full suite of ocean tracers by the repeat hydrography program has shown us the importance of repeated decadal measurements for the comprehensive detection and monitoring of ocean water mass changes. CFCs, SF_6, carbon isotopes, and tritium-helium should be core measurements of the repeat hydrography program, with the understanding that it may not be necessary to measure these tracers on all stations.

SF_6 will be an increasingly important tracer because atmospheric CFC abundances are no longer increasing with time, making it difficult to use them to investigate the ventilation of recently formed water masses. Tritium can give additional age information for deep waters (e.g., Huhn et al., 2008a). Because the surface concentration of tritium varies regionally, mixing of water masses of different origin complicates the interpretation, but this regional contrast may be useful in combination with other ventilation tracers. The tritium-helium age has also been used for dating shallow and intermediate water masses (e.g., Jenkins, 1998). As the tritium transient decays, the resolution of this technique is reduced, but it still has value in the Northern Hemisphere. Separation of the tritiogenic component from the volcanic helium-3 in the Southern Hemisphere and in deeper waters can also limit this method in certain areas. In general, the interpretation of tracer ages (whether tritium-helium, ^{14}C, CFCs, or SF_6 derived) must be done within the context of transit time distributions and appropriately constructed models. Each tracer convolves with ocean ventilation and transport processes in unique ways and therefore contributes complementary information. Thus there is value in coordinating tracer measurements on sections.

Helium-3 on its own can be used for investigating upwelling (Klein and Rhein, 2004) or the ventilation of water masses that are high in natural helium-3. Helium-4 and neon are high in ice shelf waters and may be used for investigating AABW formation mechanisms (Huhn et al., 2008b). In addition, noble gases offer some potential for characterizing ice-water interactions (Hood et al., 1998; Postlethwaite et al., 2005). Because it is produced in situ, the accumulation of helium-3 produced by the decay of bomb-tritium within the oceanic thermocline, particularly in the northern hemisphere, provides information complementary to the "ventilation tracers" such as tritium, CFCs and radiocarbon. For example, it has been used to diagnose decade time scale changes in water mass ventilation in marginal seas (e.g., Jenkins, 2008). The coupling between this helium-3 and its parent (tritium) makes it a useful diagnostic of the effective Peclet number of ocean ventilation (Jenkins, 1998), or within the context of transit time distributions, the ratio of the second to first moments. The efflux of tritiugenic helium-3 from the thermocline (or of volcanic helium-3 from the abyssal waters) provides another important diagnostic, as it traces the return pathway of remineralized nutrients to the euphotic zone, providing a "flux gauge" to estimate regional-scale new production rates (e.g., Jenkins and Doney, 2003) and their possible variations (Jenkins, 2008).

It has also become clear that many changes are driven by sub-decadal scale variability. Variations associated with climate modes can be expected to drive natural variability in ocean biogeochemistry (e.g., Jenkins, 2008), and Rodgers et al. (2009) have recently shown that it is also important to consider the potential impact of Rossby Waves on ocean biogeochemistry. An understanding of the underlying processes controlling the higher frequency variations will be critical to reducing the uncertainties, and it will be critical to link both decadal and high-frequency hydrographic data with observations from other platforms, including time-series stations and the Argo program. In addition, the close correspondence between satellite-derived sea-surface height variations and DIC inventories in the Indian Ocean offers a way by which remote sensing measurements may help reduce uncertainty in the detection of anthropogenic changes by identifying the component of the measured changes that are due to natural variability in ocean circulation.

2.4 Quantifying transports

Full-depth, trans-oceanic hydrographic sections provide the necessary data for estimates of ocean transports of heat, freshwater, and other properties on basin to global scales (Fu, 1981; Wunsch et al., 1983). Obtaining these estimates globally and improving them (albeit from a mostly steady-state circulation perspective) was a major goal driving the WOCE global hydrographic survey. Related goals included obtaining water mass formation rate and flow path estimates. More recently, work has focused on assessing temporal variability of transports and inventories of seawater properties, including carbon system and other biogeochemical parameters (see section 2.3 for additional information).

While the vertical shear of the component of horizontal velocity perpendicular to each station pair of a hydrographic section is straightforward to calculate from geostrophy, determining the absolute velocity field to sufficient accuracy for transport estimates is more problematic. Shipboard and lowered Acoustic Doppler Current Profiler (SADCP and LADCP) data are complementary to hydrographic measurements. The combination of all three provides the best constraints on measured transports. Both LADCP and SADCP data can be used to reference geostrophic current estimates and to quantify ageostrophic flow, but they have different strengths and weaknesses. SADCP sampling (continuous between stations) matches the geostrophic calculation (which is an average between stations), but covers only the upper part of the water column. LADCP sampling (full-depth profiles on station) does not match the geostrophic calculation in the horizontal, but it provides an accurate measurement of the barotropic velocity at each station. LADCP data can resolve complex velocity structure near bottom topography, and near the equator where synoptic geostrophic calculations are useless. Both methods provide context for the hydrography by showing the along-track as well as the cross-track components of the synoptic velocity field.

ADCP measurements have contributed to our understanding of ocean transports and processes on a wide variety of scales. Analysis of SADCP has revealed the deep penetration of wind-driven ageostrophic flow at low latitudes (with implications for meridional heat and other property fluxes) in all three major oceans (Chereskin and Roemmich, 1991; Wijffels et al., 1995; Chereskin et al., 1997), with the largest influence in the Indian Ocean, due to the seasonal monsoons (Chereskin et al., 2002). Decadal variability in large-scale atmospheric forcing, such as indicated by variations in the SAM, implies variability in the Ekman transport on similar time scales. Direct estimates are essential in resolving the Ekman contribution to property transports, constraining relative transport estimates, and providing direct estimates of boundary current transports (e.g. Beal et al., 2003). In addition, the absence of a level of no motion (the tendency of the near-bottom flow to resemble a weaker version of the shallow currents) has been demonstrated in many high-latitude regions such as the Subantarctic Front in the Pacific (Donohue et al., 2001) and the Bering Sea (Chen and Firing, 2006). ADCP measurements have also revealed previously unsuspected currents, leading to substantial revision of basin-wide meridional transport estimates (Beal and Bryden, 1999; Donohue et al., 2000). Aided by bottom tracking, LADCP measurements have revealed in detail the bottom-intensified outflows from the Weddell Sea (Gordon et al., 2001). Diffusivities inferred from lowered ADCP shear and CTD strain profiles (Sloyan 2005; Kunze et al., 2006) can provide additional constraints for models.

LADCP and SADCP data help to constrain transport estimates, but adjustments are still necessary to overcome noise and temporal aliasing and to balance mass or other constraints. The ocean box inverse method (Wunsch, 1978) allows adjustments to the velocity field subject to dynamical, mass balance, property transport, and other constraints. Application to single sections has led to insights into basin-wide transports including nutrients and carbon (e.g. Bryden et al., 1991; Robbins and Bryden, 1994; Macdonald et al., 2003), with coast-to-coast sections enabling various constraints such as mass or salt conservation (Tsimplis et al., 1998; Lherminier et al., 2007) to be applied to adjust measured velocities, such as from vessel-mounted ADCPs (Saunders and King, 1995) or lowered ADCPs (Joyce et al., 2001). Schott et al. (2006), and Dengler et al. (2006) provide examples how ADCP data from repeat hydrography sections can be combined with mooring data to infer the transport of the Deep Western Boundary Current and its variability.

Analysis of multiple zonal, and sometimes combined zonal and meridional sections has yielded basin and regional estimates of property transport, divergence, mixing and air-sea flux with estimates of uncertainty (e.g. Holfort et al., 1998; Sloyan and Rintoul, 2000; Ganachaud and Wunsch, 2002, 2003; Alvarez et al., 2002). The careful analysis of global hydrography and circulation (including the WOCE transects) by Reid (1994, 1997, 2003) has also provided basin-scale meridional-vertical overturn (Talley, 2003; Talley et al., 2003) and freshwater transport (Talley, 2008) estimates.

However, temporal aliasing of hydrographic sections introduces error into any steady-state analysis (e.g., Thurnherr and Speer, 2004). Ocean data assimilation, in which an ocean general circulation model and oceanographic data are brought to consistency with error estimates, addresses this problem (e.g. Yu and Malanotte-Rizzoli, 1998; Stammer et al., 2002). The Global Ocean Data Assimilation Experiment (GODAE) has fostered substantial progress in this regard. ECCO (Kohl et al., 2007) and K7 (Masuda et. al., 2006) are two examples of recent efforts. Both assimilate Argo and hydrographic data from WOCE and CLIVAR, as well as reanalysis surface flux products.

Shifts in the meridional overturning circulation (MOC) have been hypothesized to be key processes in triggering past abrupt climate changes (e.g., Broecker, 1998), and are predicted for the future (see the 4th Assessment Report of the Intergovernmental Panel on Climate Change). A regional array at 26.5°N in the North Atlantic (Cunningham et al., 2007; Kanzow et al., 2007) has been monitoring the strength and vertical structure of the Atlantic MOC since 2004, where the mid-ocean flow is monitored by an array of moored instruments along the section. The basic principle of the array is to estimate the zonally integrated geostrophic profile of northward velocity on a daily basis from time-series measurements of temperature, salinity and meridional velocity throughout the water column at the eastern and western boundaries and on either side of the mid-Atlantic Ridge. Hydrographic sections at 5-year intervals are a key component of the monitoring strategy providing independent estimates of the array and the basin-wide property distributions necessary for flux studies (Jayne and Marotzke, 2001). It is envisioned to extend this type of monitoring to other key latitudes in the Atlantic and hydrographic sections will be central to monitoring strategies there.

Hydrographic sections are at present the only direct measurements monitoring global changes in deep ocean transports and properties like a possible decadal slow-down in the southern ocean limb of the MOC suggested in the North Pacific (Kouketsu et al., 2009) and North Atlantic (Johnson et al., 2008b). Combination of the data with improved assimilative ocean models should help to detect any future shifts. We require a set of benchmark observations of the MOC that can provide the necessary full depth, continent-to-continent dynamical constraints for verifying assimilations, coupled climate model hindcasts and for ocean initialization for climate forecasts.

Emerging issues and implications for future sampling: From the WOCE and CLIVAR surveys, we have learned that observed changes in ocean circulation and transport are not driven simply by anthropogenic forcing but also by natural interannual variations or long-period oscillations. It may require many surveys over many decades to detect these trends with confidence. Where we have 50-year data sets, we observe oscillations rather than trends; for example, the 25-year freshening/salting of Indian Mode Waters. Annual and sub-annual time series in key regions will provide critical links to the repeat hydrography program.

To accurately calculate the horizontal density gradients, the spatial variation of the composition of seawater needs to be taken into account. This is now possible using the new Thermodynamic Equation of Seawater – 2010 (TEOS-10). In June 2009 the Intergovernmental Oceanographic Commission (IOC) of UNESCO endorsed TEOS-10, which provides accurate algorithms for calculating density, potential enthalpy (i.e., “heat content”) and many other thermodynamic properties of seawater. As of June 2009, TEOS-10 has superseded the 1980 UNESCO / ICES / SCOR / IAPSO / Equation of State. The new algorithms are served from the Web site www.TEOS-10.org. Part of the new thermodynamic treatment of seawater involves adopting a new salinity variable, Absolute Salinity. It is important to note that while Absolute Salinity is now the approved salinity variable for publishing in marine science, it is Practical Salinity (PSS-78) that must be reported to national databases. This is because Practical Salinity is the measured salinity variable (rather than being a calculated variable), and it is very important to maintain continuity in what is stored in databases. This way of handling salinity is analogous to the present handling for temperature; in situ temperature is measured and reported to national data centers, but research and publishing use a different temperature variable, namely potential temperature or (with TEOS-10) conservative temperature.

The algorithm that calculates Absolute Salinity from knowledge of the Practical Salinity and the spatial location should be refined on the basis of more ocean measurements. The collection of between 20 and 100 seawater samples from each long repeat hydrography section would, over several years, build up a valuable database for this purpose.

2.5 Evaluating ocean models

Ocean general circulation models (OGCMs) and coupled climate models are being used to assess the past, present and future state of the ocean. These models are increasing steadily in their complexity and resolution, as well as the number of processes that they represent. In recent decades, it has become common practice to couple biogeochemical and ecological models to the physical components of the OGCMs and climate models in order to investigate the coupling between systems. Although based on fundamental equations of physics and chemistry, these models need to make several assumptions and simplifications in order to be able to solve these equations numerically. Key issues involving uncertainties in surface forcing (momentum, heat, and freshwater) and sub-gridscale dynamics such as diapycnal and mesoscale mixing. The problems are even more significant for biogeochemistry and ecology, which are not well constrained from basic principles. As a result, all models require careful evaluation with observations before they can be used with confidence to assess past or future states of the ocean system.

Interior ocean observations of temperature, salinity, and density, together with satellite measurements of sea-surface height, have been indispensable as metrics for assessing the quality of ocean general circulation models (see e.g., Pilot Ocean Model Intercomparison Project; Sloyan and Kamenkovich, 2007; Doney et al., 2007). But these constraints alone are not necessarily sufficient to clearly distinguish among different model solutions. Gnanadesikan (1999) showed, for example, that even models with very similar density structures can have vastly different rates of ocean circulation. Only tracers that contain age information, such as CFCs, radiocarbon, or tritium-helium, can be used to assess which of these solutions are more realistic. The impact of such constraints on the model-based estimation of the oceanic uptake of anthropogenic CO_2 was demonstrated by Matsumoto et al. (2004), who showed that only a handful of the OGCMs that participated in the Ocean Carbon Cycle Model Intercomparison Project (OCMIP) were able to simultaneously model (within the uncertainties of the data) the ocean interior distribution of CFCs and radiocarbon. The models that were consistent with that constraint had a much narrower range of simulated uptake of anthropogenic CO_2 than the whole range of models, suggesting that multiple tracer constraints are essential for model validation.

Ocean interior observations of nutrients, inorganic carbon, oxygen, and other biogeochemically relevant chemicals have also proven to be invaluable constraints to evaluate coupled physical, biogeochemical, and ecological models (e.g. Najjar et al., 2007). It is decidedly difficult for such models to simultaneously fit all observations, and Najjar et al. (2007) demonstrated, for example, that the models that fit the interior ocean distribution of radiocarbon relatively well, were generally also more consistent with the distribution of other tracers.

Ocean interior observations are an important source of information for the evaluation of ocean models, especially when these models include biogeochemical and ecological components. While the focus in the past has been on the evaluation of the mean state of the ocean, one can expect that ocean interior observations will be used increasingly to also evaluate changes in the model simulated state through time; for example, are models able to simulate the response of the ocean interior distribution to important changes in surface forcing, such as forcing associated with long-term trends in the Southern Annular Modes (e.g. Lovenduski et al., 2008).

Emerging issues and implications for sampling: Ocean interior observations, particularly tracers that contain age information, are critical for evaluating OGCMs. As these models grow in complexity and include ecosystem components, the full suite of carbon and biogeochemical measurements will be needed. Bottom and deep-water production are not yet sufficiently realistic in ocean data assimilation to unchain the models from restoration to climatology in the deep ocean (Macdonald et al., 2009). As progress is made on improving models, repeat hydrographic measurements will become increasingly useful to assimilation analyses. Since repeat hydrography at present provides the only global sampling of the bottom half of the ocean, and the only global subsurface biogeochemical measurements, it will be required to constrain the assimilated deep transports of heat and freshwater, as well as those of biogeochemical properties throughout the water column.

2.6 Providing a platform for testing new shipboard sensors and providing an opportunity to deploy and evaluate other platforms

The repeat hydrographic program offers a unique platform for testing new instrument design and provides the highest quality data streams available for intercomparison and calibration.

The Argo float program routinely uses the high-quality salinity data from repeat hydrographic sections, carefully calibrated with collected water samples and standard seawater, to provide a reference for the CTD data from Argo floats, and are heavily relied upon in the delayed-mode quality control of Argo floats (e.g. Wong et al., 2003). This calibration using the repeat hydrographic salinity data stream is essential because these floats only undergo calibrations prior to deployment and are often operating in the field for years.

Temperature data from repeat hydrography are used systematically to test instruments such as the expendable bathythermograph (XBT) deployed on merchant vessels as part of the Ship of Opportunity Program (SOOP) (Goni et al., 2010). Through comparison with high-quality data, Wijffels et al. (2008) and Gouretski and Koltermann (2007) note a systematic bias in XBT observations, suggestive of a fall rate error in the XBTs. Testing for the possible mechanisms behind fall-rate errors has already begun on recent repeat hydrography cruises (e.g., along P18 and P15S). The global coverage and availability of high-quality intercomparison data are invaluable to determine if manufacturing changes in instrument systems are introducing erroneous trends or signals.

The continuing development of new sensors and instruments provides opportunities to extend the suite of parameters measured by the repeat-hydrography program. For example, full-depth un-tethered microstructure profilers that have recently become commercially available can be deployed with CTD/LADCP packages to obtain simultaneous profiles of hydrography, velocity and rate of kinetic-energy dissipation and diapycnal diffusivity, while requiring only modestly increased on-station times (e.g., St. Laurent and Thurnherr, 2007). The coverage of the repeat hydrography program could thus allow quick and efficient collection of a near-global data set of mixing in the ocean.

In addition to providing a high-quality platform to calibrate and test new instrumentation, the repeat hydrographic sections, designed for global coverage, often cross portions of the ocean that are infrequently visited by other vessels. This fact alone has resulted in this program becoming a major source for deployments of autonomous instrumentation aiming for global coverage, most notably Argo floats and surface drifters. Without these cruises, Argo floats and drifters would either have to charter dedicated ships (aircraft) - a more costly proposition - or tolerate gaps in their global array.

2.7 Underway measurements

Repeat hydrographic cruises are unique in their spatial extent, spanning basins, and in their coverage of data-sparse regions. The ships offer the opportunity to use platforms with power, laboratory space, and marine technicians and scientists who can attend measuring systems. Further, these cruises will have associated cruise documentation and data archiving, so that the quality and permanence of surface observations will garner attention and increase their use in cross-disciplinary applications. Although the current system of Data Assembly Centers (DACs) (see section 4) does collect some underway data in a systematic manner, the DACs are not appropriately resourced to handle the full suite of underway variables currently measured on research cruises. This will be a major goal for the next decade of hydrography.

Typical atmospheric underway measurements include winds, humidity, air temperature, pressure, and precipitation, radiation measurements including direct solar (shortwave) and downwelling longwave (from clouds and sky). Occasionally vessels deploy net, ultraviolet, and photosynthetically active radiation (PAR) and skin temperature sensors. Ocean measurements from continuous water sampling systems include sea surface temperature, salinity, and in some cases fluorescence and dissolved oxygen. Additional underway measurements may include atmospheric and oceanic pCO_2 (Schuster et al., 2010), total inorganic carbon and noble gases, direct fluxes (Fairall et al., 2010), radiative SST, currents (from SADCPs), and bathymetry. See Smith et al. (2010) for a complete overview.

Underway measurements from the hydrographic survey can complement the underway network on commercial ships (see Goni et al., 2010) in several areas outlined below.

Climate quality surface meteorology and air-sea fluxes of heat, freshwater, momentum

High quality in-situ observations of surface meteorology and the air-sea fluxes of heat, freshwater, and momentum have high value, and commercial vessels are beginning to measure gas and particle fluxes in a more routine way, which could also benefit from validation by research cruises. Such observations are needed for algorithm development and, if delivered in real-time, could be used to validate fields used to specify the surface forcing of the ocean, including the surface fields from Numerical Weather Prediction (NWP) models, from Atmospheric General Circulation Models (AGCMs), from remote sensing, and from blended products. They may also be used as independent, high-quality in situ observations to anchor and/or gauge the accuracy of these fields.

A number of observing programs have evolved over the past decade that focus on automated systems for oceanic and atmospheric measurements (Smith et al., 2010). To date, these programs have focused on data collection and standardization of quality control, instrument exposure, and metadata. Many underway measurements focus on air-sea fluxes and these activities are described in Fairall et al. (2010). It is worth noting that efforts are being made to consider the flow distortion by the hulls and superstructure of the research vessels and that these have been accompanied by efforts to use additional portable meteorological and flux systems to guide improvements to the placement of sensors and research vessels and thus in the quality of the data. With such ongoing attention to the performance of underway systems on the research vessels conducting the repeat hydrographic lines, there is the promise of high observational quality.

This quality can be further ensured by making use of the fact that the research vessels have long-lived installations where there is merit in dedicating time to the proper cabling, both to deliver power to sensors as well as to collect data. With the availability of power, active ventilation of air/humidity sensors should be implemented. Active ventilation and heating, as needed to cope with icing and/or dew, should be implemented on incoming shortwave and longwave sensors. If possible, radiation sensors should be roll-stabilized. Automated surface wave observations (e.g., from ship-borne wave records or wave radars) would enhance the utility of the surface meteorological and air-sea flux sensors.

Where repeat hydrographic cruises go to regions with either very low winds speeds (less than 3 m/s) or high wind speeds (greater than 15 m/s), consideration should be given in planning these cruises to include a research group able to make turbulent flux measurements. These high-value data from undersampled wind regimes will allow refinement of flux methods.

Underway oceanographic and meteorological sampling

Thermosalinographs should be operated and attended to maintain quality, including annual factory calibrations following established international protocols (Smith et al., 2010; Fairall et al., 2010). Underway fluorescence should also be measured. Underway ADCP sampling yields velocity profiles in the upper ocean (100-1000m, depending on the instrument type used). Where possible, consideration should be given to use tethered XCTDs, XBTs, and/or similar techniques to obtain the thermohaline structure of the upper ocean to accompany the underway ADCP data. This will not only quantify the depth and spatial variability of the mixed layer but can also be used to yield information on vertical mixing near the sea surface. As sampling methods advance, underway sampling should consider sampling of DMS (dimethyl sulfide), total inorganic carbon, total alkalinity, pH (Wang et al. 2007), and O_2/Ar by mass spectrometry (Cassar et al., 2009).

It would be valuable to use repeat hydrography surveys to sample the lower atmosphere in data-sparse regions. Smith et al. (2010) address the interest to develop and/or improve underway sensors for cloud identification, waves (Swail et al., 2010), shipboard radar (for wave parameters and precipitation), and surface radiation.

Carbon dioxide

Surface pCO_2 measurements from hydrographic cruises can serve as reference data since measurements are made in a controlled environment with comparison to other carbon parameters. High-quality surface pCO_2 measurements, when combined with other surface and sub-surface parameters, can improve mechanistic understanding of processes controlling surface CO_2. As with surface meteorological fluxes, hydrographic cruises cover regions of the ocean never sampled by commercial vessels or moorings, and can add invaluable insights and constraints on surface CO_2 variability. Hydrographic cruises also offer a unique platform for the development of robust and automated sensors for other carbon system parameters. The lack of such sensors is currently a major limitation in developing an adequate observing capacity for surface CO_2, air-sea CO_2 flux, and ocean acidification (Schuster et al., 2010).

3. Strategy

3.1 Temporal and spatial sampling

In developing an integrated and interdisciplinary framework for ship-based repeat hydrography, it is important to consider the time scales of variability of the phenomena under investigation. For example, repeat occupations at decadal intervals are mostly appropriate for the characterization of the uptake of transient tracers, such as bomb radiocarbon, as these inventories are expected to change smoothly with time. For the detection of changes in the anthropogenic carbon inventories, one is challenged by two opposing constraints. One the one hand, the limits for the detection of changes in anthropogenic CO_2 are 8-10 years for most regions (see Levine et al., 2008), so that a decadal repeat frequency seems adequate. On the other hand, changes in the natural carbon cycle occur on shorter temporal intervals, requiring higher frequency sampling. Since both (natural and anthropogenic) signals are present in the measured dissolved inorganic carbon fields, one would therefore infer a need for higher frequency sampling. However, the availability of ancillary observations, such as sea-surface height, may substantially relax this requirement, so that an approximate decadal repeat frequency could be sufficient for determining the changes in the oceanic inventory of anthropogenic CO_2. A more detailed assessment requires a dedicated sampling study. For other goals, a decadal survey is clearly less appropriate. For example, the quantification of transport changes requires higher frequency sampling since it is known to have substantial interannual variability. While the Argo program will resolve some of these issues for physical variables in the upper 2 km, it does not currently sample deeper than 2 km or in areas with ice cover. Another factor is the need for approximate synopticity on basin scales and the constraint that cruises are carried out on a rolling basis, based either on funding cycles, ship schedules, or a deliberate strategy of trying to carry out several cruises each year in order to capture special events that might occur. A high-frequency survey in addition to the decadal survey would be effective to reduce the biases in some regions, such as the western boundaries, where the basin-scale dynamic response signals are strong, and high-latitude areas where property concentrations/inventories are affected by short-term climate variations through water mass formation.

Taking into account these considerations, two types of surveys are presently required to meet scientific objectives: (1) decadal surveys and (2) a sub-set of the decadal survey lines sampled at high frequency (repeats every 2-3 years), ideally, repeats of lines sampled in the past decade. To capture the change within a quarter or shorter period of the decadal time scale, the decadal repeat survey requires full basin synopticity over a < 3 year period (beginning in 2012). Both surveys should be initiated no later than 2012 to ensure continuity following the termination of the current CLIVAR survey.

This level of synopticity may become less necessary as assimilation techniques develop, but is currently necessary to distinguish between spatial and temporal variability. The Argo program provides a crucial complement to hydrographic section data, a synergy that has not yet been fully exploited. With the logistical difficulties of obtaining large-scale synoptic snapshots of basin dynamics and properties, it is imperative to develop methods of normalizing section data to a common year, and in some cases, over 10-year scales, without introducing significant biases. These techniques do not yet exist, and use of high-frequency Argo data and data assimilation methods will be increasingly important to develop the required methods.

The survey to begin in 2012 will take into consideration the sampling schedule carried out during the CLIVAR program in order to ensure decadal repeat frequency for each basin as much as possible. For example, the Atlantic was sampled most densely between 2003-2005, the Pacific between 2005-2007, and the Indian in 2007-2009, implying that the first post-CLIVAR survey should start with the Atlantic from 2012-2014, the Pacific from 2015-2017, and the Indian from 2017-2019.

Spatial sampling should follow past surveys, with major efforts carried out in the Atlantic, Pacific, and Indian oceans, with the Southern Ocean integrated as part of the other basins. The Arctic is of increasing importance and should be emphasized, either as a separate effort or a coordinated effort from Atlantic and Pacific basin efforts.

Ideally, sections should extend from coast to coast, or coast to ice, follow standard WOCE lines with small modifications as necessary for territorial waters, ice coverage, etc., and maintain the standard WOCE sampling strategy.

Horizontal resolution:

- Physical measurements: nominal 30 nautical mile spacing with higher resolution in regions of steep topography and boundary currents.
- Carbon measurements: carbon and tracers at 60 nautical miles or better.

Vertical resolution: full water column.

It is also recognized that several open-ocean hydrographic programs exist that do not meet the sampling resolution criteria outlined by the GO-SHIP Panel or are one-time hydrographic surveys with no commitment for repeats. As with the WOCE programme, which was composed of both repeat sections and one-time surveys, the GO-SHIP Panel recommends that all hydrographic sections meeting minimum criteria (see below) be included as part of the global hydrographic program. Broad participation in the hydrography program will facilitate standardization of methods, data management and sharing, and integration of all appropriate ocean interior data in data synthesis activities.

3.2 Core variables

For the decadal survey, the core program lines should measure

- temperature, salinity, and pressure
- oxygen, phosphate, silicate, and separate measurements of NO_2 and NO_3 if possible; otherwise, NO_2 + NO_3 (with clear reporting of what was measured)
- at least 2 carbon parameters (e.g., DIC, Alkalinity, pCO_2, pH), where DIC and Alkalinity are the preferred pair, but spectrophotometric pH is a useful 3rd parameter because of high measurement precision and growing interest in ocean acidification.

- carbon isotopes (^{13}C, ^{14}C), chlorofluorocarbon tracers (CFC-11 and/or 12) and SF_6; tritium and helium-3 should also be measured on key sections, including meridional sections P10, P16, P18, I06S, I08, I10, A16, A22, A20, and zonal sections I05, P06, P04, and A24).
- shipboard and lowered ADCP

Salinity and oxygen should also be measured on every bottle. Also recommended are organic carbon parameters (POC, DOC) and underway surface measurements (including pCO_2, pigments, and related biological parameters at the surface). By 2012, microstructure measurements from profilers may also be considered for routine application during the next decade of hydrography. A certain subset of trace elements and isotopes should be included in future high-frequency repeat sections, particularly for parameters to deduce atmospheric mineral dust deposition to the surface ocean in key areas.

For bio-opical measurements, GO-SHIP endorses the recommendations of the International Ocean-Colour Coordination Group, including the following parameters:

Instruments to be added to a profiling CTD:

- Fluorometer to measure chlorophyll fluorescence
- Transmissometers and/or light-scattering sensors and nephelometers to measure particle beam attenuation coefficient
- PAR sensor (where possible)

Water samples collected for the following measurements:

- Chlorophyll-*a* (Turner Fluorometer)
- HPLC pigments
- Phytoplankton absorption
- CDOM (desirable measurement)
- Flow cytometry

Many of the above samples can be stored in liquid nitrogen for later analysis back in the laboratory.

On deck measurements:

- Continuous recording of incoming photosynthetically-active radiation (PAR), using a PAR sensor with a data logger (automatic).
- Measurements of spectral reflectance using a hyperspectral hand-held radiometer.

Several ancillary observations should be made whenever possible. The repeat hydrographic ships should make surface meteorological observations, following the guiding principles of the WOCE hydrographic program described in the handbook by Bradley and Fairall (2006). The observations should include wind speed and direction (relative to the ship and corrected to absolute), air temperature and humidity, sea surface temperature, rainfall, barometric pressure, incoming shortwave radiation, and incoming longwave radiation. Several bio-optical measurements are also highly desirable, including profiling underwater spectral-radiometer measurements and photosynthesis-irradiance experiments.

It is also suggested that each cruise should collect between 20 and 100 seawater samples (150ml plastic bottles) for the direct measurement of density in the laboratory, in order that the effect of the spatial variation in the composition of seawater can be estimated. The 150ml bottles would be sent to a laboratory where their density (at the laboratory temperature and pressure) would be measured with a vibrating tube densimeter along with the sample's Practical Salinity. The same laboratory procedure would be applied to some ampoules of standard seawater as a check on the laboratory procedure and as a check of the stability of the standard seawater ampoules.

For the high-frequency/other sustained repeat lines, T, S, O_2, and nutrients should be measured as the minimum core variables, as well as any other variables useful for understanding subdecadal-scale variability. The target vertical spacing for these lines can be selected according to the water masses under investigation. However, during the decadal survey period in each ocean basin, the high-frequency lines should be carried out using the same specifications as the decadal survey in order to construct a uniform data set over the whole basin.

For one-time or non-core survey lines, sections should be open-ocean, adhere to the data sharing policy (below), and follow the criteria for high frequency lines.

3.3 Sustained repeat lines

The table and map below outlines the repeat sections felt to be most critical for the decadal survey (solid lines, black text) and the high-frequency repeat lines (dashed lines, red text). Many of the lines, both decadal and high-frequency, represent sections that already have on-going national commitments for implementation. Several of the lines represent sections that are important for science goals, although may not be possible owing to problems with territorial waters or ship resources. The lines shown here are the minimum thought required for a global periodic survey. Additional lines would help to meet many other program goals.

The program design calls for zonal sections at mid-latitudes in all the major ocean basins, locations where the ocean transports of heat and carbon are near their maximum. Zonal lines in the sub-polar regions and the tropics are designed to capture maximum freshwater transport by the ocean. The meridional lines, at least one through each set of ocean basins, are ideal for inventory studies of ocean properties such as heat and CO_2. Sections also cross the Antarctic Circumpolar Current at various chokepoints around the globe to facilitate studies of inter-ocean transports, including both limbs of the meridional overturning circulation. In addition, sections around Antarctica and in the northern North Atlantic Ocean allow monitoring of outflows of bottom and deep water just downstream of their formation regions, as well as upwelling of warm deep waters that may be critical to understanding changes in the cryosphere. Finally, some Arctic sampling is essential, as recent changes there are dramatic.

Atlantic	**Pacific**	**Indian**	**Arctic**
A22 and A20	**P01**	I09 N and I08 S	Barrow to Svalbard line (done on the Healy and Oden in 2005)
A16 N and S	**P02**	I09 S	**75 N**
A13.5	P04	I07N	**RUSALCA**
A21	**P13** (maybe 14)	I05	**Davis Straits**
A01W	**P09 / P10**	I06S	**Barrow Straits and Nares Straits**
AR07E (A01E)	P06	I03	
A24N / A05	**SO4P** (modified / Ross Sea)	**I10** (if possible)	
A02	P15 S (Equator to 67 S when possible)	S04I to I09S (needs to connect to S4P)	
A10	P18	**I01 W and E**	
A12 / SRO4 (Weddell Sea line)	P16 N and S		
A25 (OVIDE)	**SR03**		
	P14N (Aleutians and up)		

Table 1. Recommended hydrographic sections for the sustained decadal survey (black text) and high-frequency repeat lines (red text).

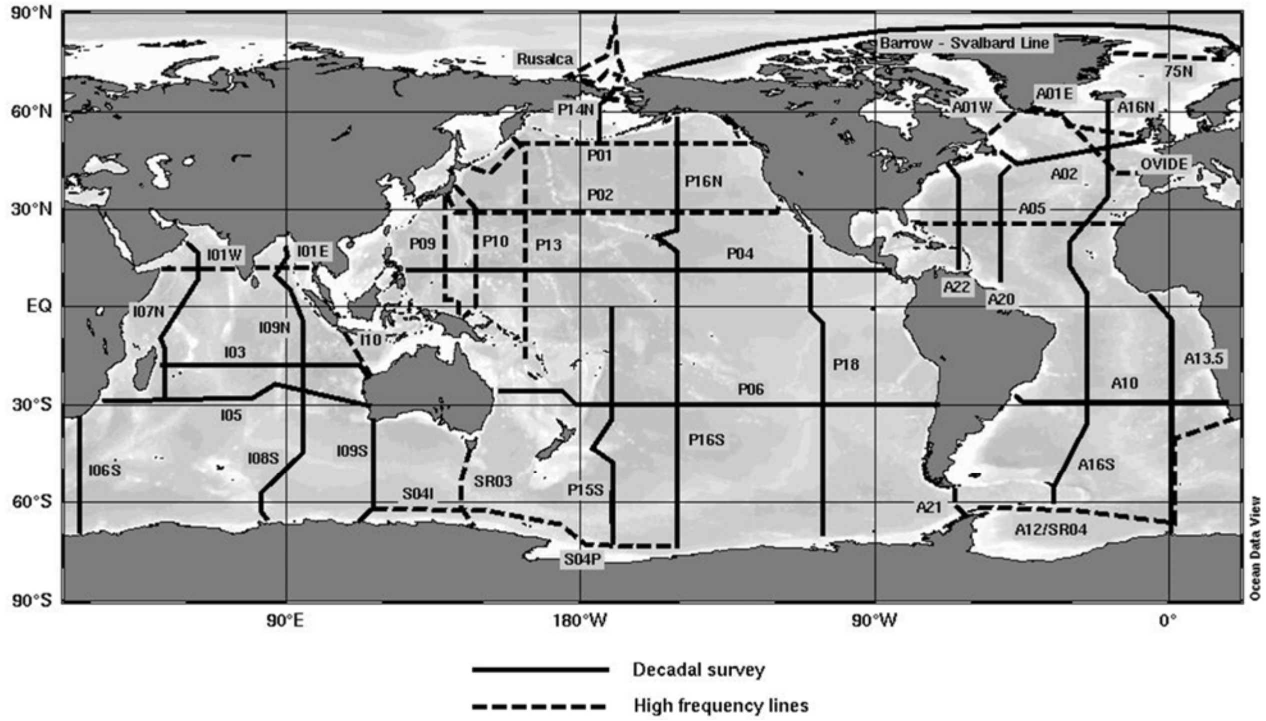

Figure 4. Recommended hydrographic sections for the sustained decadal survey (solid lines) and high-frequency repeat lines (dashed lines).

3.4 Quality assurance practices

To detect statistically significant decadal changes in any property field requires high- quality data. Not only are high precision and accuracy necessary, but also knowledge of the uncertainty in the reported numbers. As part of the GO-SHIP effort to reach the highest possible data quality, the 1994 WOCE hydrographic program manual is being revised and should be published in early-2010. These references will provide details of best practice for each of the variables to ensure comparability of measurement programs. Similarly, the use of certified reference materials (CRMs) is very helpful in improving data quality and should be used as frequently as necessary to reach the highest possible data quality. For alkalinity and DIC the use of CRMs is now a common practice that has increased the quality of measurements significantly. Much effort is being put into the development of CRMs for nutrients (Aoyama et al., 2009). Efforts to provide CRMs for other parameters, such as oxygen and pH are underway. Using these materials on all repeat hydrography cruises will solve a key problem by enabling the relative accuracy of the measurements to be maintained between cruises.

4. Data Management, Sharing, and Product Development

The general strategy proposed for data management is to better support and coordinate the existing data assembly and archive centers, to develop new tools and centers to manage the increasing variety of properties observed on hydrographic lines, to coordinate data management activities with those of the operational programs such as Argo and OceanSITES, and to improve technology and data policies to release data in a more timely manner.

It is also proposed to develop a single international information center for repeat ship-based hydrography that will serve as a central communication and coordination forum and include a portal or directory to the data assembly centers.

4.1 Data sharing and release policy

While it is important to protect individual scientific interests and investment of effort by investigators, evolving towards a more operational system will be essential for justifying a sustained program with national funding support, and closer coordination with the operational programs may require some changes to data-release practices. For example, in the next-generation hydrographic program, it may be possible to implement real-time or near real-time CTD data release using Argo technology. Near real-time data release of underway carbon and other semi-automated biogeochemistry measurements may also be possible through closer coordination with the Global Ocean Surface Underway Data Project (GOSUD) and the Shipboard Automated Meteorological and Oceanographic System (SAMOS) programs, which have developed a data management system for real-time surface temperature and salinity data from research ships.

At present, the GO-SHIP panel recommends the following data-release guidelines:

- Preliminary dataset released within 6 weeks (e.g., all data measured on the ship)
- 6 months for final physical data
- 1 year for final data of all other variables (except for isotopes or tracers with shoreside analysis where 1 year is difficult).

The relatively rapid release of data is motivated by their usefulness for climate studies, which are of increasing societal importance. Some countries are already following these guidelines. However, to facilitate rapid release of data by all participants, a system should be developed to appropriately recognize the efforts of data contributors. While having data contributors participate in synthesis activities for co-authorship could resolve some issues of ownership, ultimately the international research community needs to evolve to the point that data are released as soon as possible without waiting for a 2-3 year synthesis activity. Establishing community-wide practices to standardize how to appropriately acknowledge data contributors may help some participants to accelerate their current data-release practices. One solution that should be adopted immediately is to publish the Final Cruise Reports in the journal *Earth System Science Data* (ESSD) with all participating PIs as authors.

4.2 Data assembly and archive centers

Several data centers currently provide data management services for particular types of hydrography data. However, to meet the needs of a sustained global program, data assembly centers will need dedicated staff time and new funding, and will need to be increasingly integrated with the data management systems for other sustained programs such as Argo and OceanSITES. The challenges of such integration, both operationally and financially, should not be underestimated, but without this level of support for the data centers, a globally coordinated hydrography program with regular deliverables will not be possible.

The list below provides information about the mandate of each DAC during the CLIVAR program.

1. CTD and bottle data

   CLIVAR and Carbon Hydrographic Data Office
   Principal Contact: Jim Swift, Director
   Email: jswift@ucsd.edu
   Web site: http://cchdo.ucsd.edu/index.html
   Responsibilities : The fundamental role of the CCHDO at the University of California San Diego Scripps Institution of Oceanography is to ensure that WOCE Hydrographic Program data, CLIVAR repeat hydrography data, global ocean carbon hydrographic data, and other similar CTD/hydrographic data and their associated documentation are prepared and made available for both immediate use and a long service life. The CTD, hydrographic, and tracer data used in large-scale ocean circulation studies are brought together, verified, corrected for content and format errors, assembled with relevant documentation, and carefully prepared for dissemination and archive. CDIAC carries out all data management functions for CO_2-related data and the CCHDO handles these functions for the CTD, hydrographic, and tracer data. The CCHDO merges into its data files the latest versions of the CO_2-related data as received from CDIAC.

2. Discrete Carbon Data

   Carbon Dioxide Information Analysis Center - Ocean CO_2 (World Data Center for Atmospheric Trace Gases)
   Principle Contact: Alex Kozyr
   Email: kozyra@ornl.gov
   Web site: http://cdiac.esd.ornl.gov/oceans/home.html
   Data: http://cdiac.esd.ornl.gov/oceans/RepeatSections/clivar_introd.html
   Responsibilities: Since 1993, CDIAC has been serving the ocean scientific community as the central repository for the carbon dioxide data measured on the WOCE/JGOFS cruises. CDIAC receives WOCE hydrographic and tracer data from the WHPO. Thus all US and most foreign WOCE hydrographic, chemical and carbon data are available now through the CDIAC Ocean data web page. Most of the data at CDIAC are available as published and electronic Numeric Data Packages (NDPs). The CDIAC_WOCE Ocean Data View (ODV) Collection that includes all WOCE sections with CO_2 measurements as well as hydrographic and nutrient measurements is now available through the CDIAC Web site. CDIAC communicates frequently with the scientific measurement groups and individual PIs. This has helped CDIAC build the largest atmospheric and oceanic carbon data sets in the world, with the highest quality data. As the new carbon data measurements will be measured by groups on the repeat hydrographic sections, CDIAC is ready to continue its support to the CCHDO in CO_2 data processing and archival. CDIAC and the CCHDO cooperate closely: CDIAC receives many CO_2-related data files directly, and also some from the CCHDO. CDIAC carries out all data management functions for CO_2-related data and the WHPO handles these functions for the CTD, hydrographic, and tracer data. The WHPO merges into its data files the latest versions of the CO_2-related data as received from CDIAC. CDIAC uses the latest versions of the hydrographic data in its files. The CCHDO is the primary provider of hydrographic data to NODC/WDC-A. Both facilities distribute data in formats agreed to be their user communities.

3. Shipboard ADCP

   ADCP Data Archive at the Japan Oceanographic Data Centre (JODC), Japan
   Principal Contact: Yoshiharu Nagaya
   Email: ynagaya@jodc.go.jp
   Web site: http://www.jodc.go.jp/goin/clivar.htm

Data: http://jdoss1.jodc.go.jp/cgi-bin/2001/feti_vector
Responsibilities: Shipboard ADCP data. The ADCP Data Archive at the JODC, together with the Hawaii Joint Archive for Shipboard ADCP, is co-responsible in seeking out CLIVAR principle investigators and data contacts for calibrated and quality-controlled shipboard ADCP datasets.

and

Hawaii Joint Archive for Shipboard ADCP, USA
Principal Contact: Patrick Caldwell
Email: Patrick.Caldwell@noaa.gov
Web site: http://ilikai.soest.hawaii.edu/sadcp/clivar.html
Data: http://ilikai.soest.hawaii.edu/sadcp/main_inv.html
Responsibilities: Shipboard ADCP data. The Hawaii Joint Archive for Shipboard ADCP, together with the ADCP Data Archive at the JODC, is co-responsible in seeking out CLIVAR principle investigators and data contacts for calibrated and quality-controlled shipboard ADCP datasets.

4. Lowered ADCP

LADCP Data Assembly Centre, LDEO, USA
Principal Contact: Eric Firing, University of Hawaii
Email: efiring@hawaii.edu
Web site: http://currents.soest.hawaii.edu/clivar/ladcp
Data:
http://kage.ldeo.columbia.edu/SOURCES/.LDEO/.ClimateGroup/.PO/.LADCP/
Responsibilities: Lowered ADCP data from CLIVAR cruises (currently only US cruises using LDEO processing software). Discussions are on-going to determine if the US NODC could manage national and international LADCP data.

5. Surface Meteorology

Surface Marine Meteorological Data Assembly Center, COAPS, FSU
Principal Contact: Shawn R. Smith
Email: smith@coaps.fsu.edu
Web site: http://www.coaps.fsu.edu/RVSMDC/CLIVAR/
Data: http://www.coaps.fsu.edu/RVSMDC/html/data.shtml
Responsibilities: The CLIVAR Surface Marine Meteorology Data Assembly Center (DAC) is established at the Center for Ocean-Atmospheric Prediction Studies on the campus of Florida State University. The mission of the DAC is to collect, quality control, distribute, and assure archival of underway surface meteorological observations from CLIVAR hydrographic cruises. Additional surface meteorology data will be accepted from CLIVAR-sponsored experiments in the marine environment. Data will be accepted from any hydrographic program willing to provide their data to the DAC. This data center will accept data submissions from research vessels and moored buoys from continuously sampling automated weather systems. Resource limitations only allow the DAC to redistribute data from CLIVAR hydrographic cruises in the native format received from the chief scientist or vessel operator. No reformatting or quality assessment is currently supported. The exception is data received from vessels that contribute to the Shipboard Automated Meteorological and Oceanographic System (SAMOS) initiative (Smith et al., 2010) that happen to be conducting a repeat hydrographic cruise.

6. Underway Data

The Global Ocean Surface Underway Data Pilot Project (GOSUD)
Principal Contact: Robert Keeley and Loic Petit de la Villeon

Email: Robert.keeley@dfo-mpo.gc.ca and Loic.Petit.De.La.villeon@ifremer.fr
Web site: http://www.ifremer.fr/gosud/
Responsibilities: GOSUD works to collect, process, archive and disseminate, in real time and delayed mode, sea surface salinity and other variables collected underway by research and ships of opportunity. The GOSUD project works closely with SAMOS (see also Surface Meteorological data, above). The SAMOS initiative is working to improve access to calibrated, quality-controlled, surface marine meteorological data collected in-situ by automated instrumentation on research vessels (primarily) and merchant ships. GOSUD focuses on the collection, quality evaluation, and distribution of near-surface ocean parameters (salinity and sea temperature) from vessels. At present, the system is operational for temperature and salinity on 17 research vessels, and the GOSUD/SAMOS group is working with the International Ocean Carbon Coordination Project to determine how to include ocean and surface carbon measurements in the system.

Carbon Dioxide Information Analysis Center - Ocean CO_2 (World Data Center for Atmospheric Trace Gases)
Principle Contact: Alex Kozyr
Email: kozyra@ornl.gov
Web site: http://cdiac.esd.ornl.gov/oceans/global_pco2.html
Responsibilities: CDIAC Ocean CO_2 is managing all underway carbon data from hydrographic research ships. The data are simply archived and disseminated as received. The Surface Ocean CO_2 Atlas (SOCAT) project (data compilation carried out by the Bjerknes Centre for Climate Research, Norway) has compiled all publicly available surface CO_2 data from 1968 to 2007 into a common format dataset composed of more than 2100 cruises from 14 countries, with 7 million measurements of various carbon parameters. The SOCAT dataset is currently undergoing 2nd level quality control and will be published in 2009. It is intended that this compilation will be regularly updated to include all new surface pCO_2 data. In the future, real-time or near real-time data may be linked with the GOSUD/SAMOS project.

4.3 Data products and joint synthesis activities

Development of international synthesis activities must address new realities of working within the framework of a sustained observation program that has no “sunset clause”, but which will have a requirement to produce scientific products on a time scale that is much shorter than the traditional 10-year approach carried out by global research programs in the past. The repeat hydrography program will need to continually justify its value through publications and data products, and while analyses of individual and small groups of investigators will play a valuable role in this regard, development of a mechanism for data syntheses should also help to address these needs.

Data syntheses activities should be driven by the science. Data syntheses are only successful when there is a clear science issue to be resolved through standardizing and merging of basin- and global-scale datasets. Ship-based repeat hydrography data will increasingly be synthesized with data from other platforms and models to address specific scientific issues, which requires a bottom-up science approach rather than a top-down data management approach. It should be noted that synthesis activities will require additional funding to support data quality control, compilation, and PI meetings. It will also require the development of standing synthesis groups that meet regularly, both in basin groups and across basins. To ensure that these groups are implemented on a regular and rolling basis, it will be important for them to be managed through a sustained global coordination effort or program rather than a time-limited research program.

Data syntheses have typically been carried out starting with a basin approach since this is a convenient scale to define many scientific issues. Basin groups developed in WOCE/JGOFS and CLIVAR already exists for most areas. Building on this approach, GO-SHIP recommends 4 groups:

- Atlantic (including the Arctic)
- Pacific
- Indian
- Southern Ocean

Based on recent synthesis activities that were conducive to both science and contributing to the development of a continuously growing global synthesis (e.g., the Carbon in the Atlantic Project, the Global Ocean Data Analysis Project, the North Pacific Synthesis Project), GO-SHIP proposes a 3-step approach for basin syntheses that brings together interdisciplinary science, the data synthesis activity, interpretation, and product development:

1. For each basin, develop a science workshop to bring together observations, models, and ideas around a particular science issue that sets the framework for the data synthesis activity. These issues will evolve over time with the science and with the state of the observing system, and may include topics such as the value of adding new biogeochemical sensors to profiling floats, looking at what we know about decadal variability, comparisons between observations and models, or using models to evaluate interpolation methods and to bridge the considerable spatial and temporal gaps between repeat lines. This would involve (and may be led by) existing global or regional research programs, where appropriate.

2. From these basin-scale workshops, develop a list of the collaborative projects to be carried out to address the science issues, and establish a working group that will carry out the necessary data synthesis activities. Technical coordination groups such as the IOCCP, the Ocean Observations Panel for Climate (OOPC), the North Pacific Marine Science Organization (PICES) Carbon and Climate Group (Pacific), and research program-based groups such as CarboOcean (Atlantic), and the CLIVAR Basin Panels could provide support for these activities.

3. Hold smaller follow-up workshops to present results and outline product development, including scientific journal articles (e.g., papers contributing to a special issue of a journal) as well as publication and release of the data synthesis and merging these data with the global dataset.

This 3-step procedure for each basin should take no more than 2-3 years from first workshop to final product delivery to be able to show continued progress and justification of the continued program. A process like this would provide flexibility for science issues to evolve over time and foster integration among a wide range of communities (physics, biogeochemistry, observationalists, modelers, etc.). Moreover, it would also provide a more sustained and continual framework for producing coordinated basin- and global- scale data products on a regular basis. It should be noted, however, that new resources would need to be found to support the working groups and workshops, as well as data handling.

4.4 Development of an international communication and coordination forum

Having up-to-date and comprehensive information is crucial to plan, implement, and coordinate global hydrography. At present, there are several Web sites providing information about particular aspects of ship-based repeat hydrography. What is lacking is a common international information and communications forum to facilitate field program planning, agreements on standards and methods, and data sharing/synthesis activities.

GO-SHIP recommends the development of a single Web site that will serve as a central communication and coordination forum for both physical and carbon/biogeochemistry aspects of ship-based repeat hydrography. Along with the site, an email list should be developed to improve communication among the various groups. A Web site will be developed jointly by CLIVAR and the IOCCP for community review and launch in late 2009. Elements of the site will include:

- Cruise plans (maps, tables, contact information)
- Data directory
- Hydrography Manual
- Reference Documents (data policies, national / global research program strategies, etc.)
- Summary of synthesis activities and research programs
- Calendar
- News / Bulletin Board

The sponsors of GO-SHIP are committed to working with the international community to develop a sustained coordination activity and to seek endorsement from appropriate international and intergovernmental organizations for repeat hydrography to become a recognized part of the global observing system.

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