PROGRESSING TOWARDS GLOBAL SUSTAINED DEEP OCEAN OBSERVATIONS

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DESCRIPTION

The deep ocean plays a crucial role in aspects of the climate system on longer time-scales including the global heat budget, sea level rise, potential variations in the meridional overturning circulation, and long-term storage of climatically relevant compounds such as CO_2. Expanding the ocean observing system towards being truly global will include adequately measuring the half of the ocean volume below 2000 m depth. This will require an increased commitment to the design and implementation of technologies for collecting deep ocean data and transmitting these data to shore in a cost effective manner. This paper focuses on four of the fundamental areas where improvements to the observing system in the deep ocean are critical to the advancement of our understanding of climate science. These include deep circulation with an emphasis on “strong flows”, ocean heat content, fresh water/salinity content, and CO_2 content. It is clear that to continue working towards understanding of climate variations and their impact on society, it is imperative to maintain existing observing systems while improving and expanding the deep ocean components of the Global Ocean Observing System. Recommendations are provided for expanding the observing systems for deep circulation, for deep temperature and salinity variations (hence heat and fresh water estimates), and for deep observations of CO_2 and other chemical tracers. Recommendations are also provided in areas where technological advances are required to improve the ability to collect this data remotely using either free-floating or fixed observing platforms.

1. INTRODUCTION

As the global ocean observing system moves closer towards the goals set in OceanObs'99, one area where improvements are still greatly needed is deep ocean observations. Most of the components of the present observing array have been focused on the upper ocean, which is appropriate for climate studies on seasonal to interannual time-scales. Roughly, half of the ocean is below 2000 m, however to date this large fraction of the ocean is seriously under-sampled. In the present observing system, deep ocean observations are sparse in both space and time. This sparseness is not the result of a lack of effort or interest on the part of the community, but rather is due to both the technical challenges of deploying and maintaining instruments in the deep ocean and the high costs of ship time associated with collecting data and servicing instruments.

The deep ocean plays a crucial role in aspects of the climate system on longer time-scales including the global heat budget, sea level rise, potential variations in the meridional overturning circulation, and long-term storage of climatically relevant compounds such as CO_2, among others. Time series observations of adequate length, such as the Denmark Straits overflow measured by several European countries and the basin-spanning circulation observations collected through the joint United States-European program at 26°N (RAPID/MOCHA/WBTS (UK Natural Environment Research Council Rapid Climate Change Programme/Meridional Overturning Circulation and Heatflux Array/ Western Boundary Time Series), have demonstrated the critical importance of observing the full water column [7]. Recent repeats of hydrographic sections around the globe have shown climatically important abyssal signals in waters with Antarctic origin: warming in the southern Indian, western Atlantic, and entire Pacific Ocean as well as freshening of these waters near their source regions, and regional penetration of anthropogenic CO_2 in the South Pacific and the South Atlantic. Properties of Labrador Sea Water (LSW) and Nordic overflow waters have substantially changed on a decadal time-scale mostly due to the regional North Atlantic Oscillation-related climate variability (e.g., [1], [2]). However, the data available to study these changes are remarkably sparse and the full spatial extent and temporal characteristics of these anomalies remain virtually unknown.

Expanding the ocean observing system towards being truly global (including adequately ensuring the half of the ocean volume below 2000 m) will require an increased commitment to the design and implementation of technologies for collecting deep ocean data and transmitting those data to shore. This paper focuses on four of the fundamental areas where improvements to the observing system in the deep ocean are critical to the advancement of our understanding of climate science. These include deep circulation with an emphasis on "strong flows", ocean heat content, fresh water/salinity content, and CO_2 content. Here we discuss why observations are needed, how these observations could best be obtained, and a draft plan of recommended implementation locations.

2. DEEP CIRCULATION

Due to their huge heat capacity, the oceans provide the "long-term memory" for the climate system. However, for many years it was assumed that only the near-surface layer, directly in contact with the atmosphere, was important to the overall climate system. This assumption led to a focus in the OceanObs'99 conference on the upper 1000 m of the ocean and led to improvements of the velocity and circulation observing systems in the upper ocean. For most short time-scale processes, this near-surface focus is probably valid. However, subsequent research has indicated that climate changes on the scale of several decades to millennia are strongly controlled by both surface and deep ocean currents (e.g. [3]). Full-water-column ocean circulation changes have been linked to a wide range of climatic variations that are of clear and critical interest to society, such as global carbon sequestration and redistribution, rainfall rates, surface air temperature over land and hurricane development (e.g. [4], [5] and [6]).

Long-term velocity observations in the deep ocean are limited, and there are regions in all of the major ocean basins where no observations of deep currents exist. One of the most prominent long-term oceanic climate signals is the meridional overturning circulation (MOC; Fig. 1), which is discussed in detail in another white paper in this volume [7].

The lower limb of the MOC, the Deep Western Boundary Current (DWBC), is one of the largest climate signals in the deep ocean (e.g. [8]). Despite its importance, however, long-term repeated direct velocity observations of the DWBC in the Atlantic exist only at four locations, all of which are in the North Atlantic: at the Grand Banks near 42ºN, off Cape Cod at about 39ºN, east of the Bahamas at 26.5ºN, and at 16ºN near the Lesser Antilles. After crossing the equator into the South Atlantic, the DWBC continues along the coasts of the Americas, at times as a combination of migrating eddies [9] and continuous flow, and eventually near 38ºS it meets an also southward flowing branch of the ACC as the Malvinas Current return flow.

The resulting strong southward flow significantly alters the northward heat transport. However, only limited measurements of this flow are presently available, and they are based on short-term mooring arrays [10], [11] and [12]. In addition to the Atlantic DWBC, other deep velocity measurements have been made in select choke-point regions over long time periods, such as in the Drake Passage and the Denmark Straits overflows. However, the fate of these deep flows is poorly known once they depart from the choke-point regions and move into the basin interiors. Roughly, equivalent volumes of dense water sink in the North Atlantic and Antarctic limbs of the MOC [13], [14], and are transported to distant ocean basins [15].

Unfortunately, few long-term direct velocity measurements have been made in the deep boundary currents exporting Antarctic Bottom Water (AABW). Deep observations do exist in certain locations, most notably in choke-points such as the Vema Channel in the South Atlantic [16], the Romanche Fracture Zone in the equatorial Atlantic [17], the Samoan Passage [18], east of New Zealand at 32°S in the South Pacific [19], Wake Island Passage [20], the Mascarene Basin [21], and the southern Perth Basin in the Indian Ocean [22].

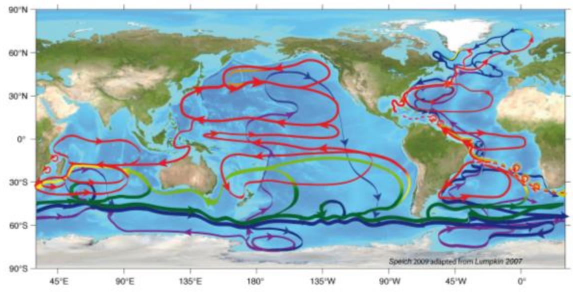

Figure 1: Schematic of the world ocean meridional overturning circulation. Red is surface flows, blue and purple are deep flows, and yellows and greens represent transitions between depths.

Currently there are very few long-term records of AABW-carrying currents. A recent two-year record from the deep western boundary current (DWBC) east of the Kerguelen Plateau in the S. Indian Ocean shows strong abyssal velocities (mean > 20 cm s-1) and a mean transport of 12 Sv of AABW, suggesting that these poorly-measured DWBCs are significant contributors to the global abyssal circulation (Fukamachi, personal communication). Abyssal topography is often sufficiently complex that to properly study and model deep currents requires observations not only at the boundaries, but also along the flanks of mid-ocean ridges and in deep trenches. To better model and understand the deep circulation, and its role in sequestering heat and anthropogenic CO_2, it is clear that more observations in the deep ocean will be required. Climate prediction models that presently exist have serious limitations as they poorly reproduce the circulation in the deep ocean as compared to the limited observations that are available.

3. OCEAN HEAT CONTENT

Quantification of ocean heat storage and its variability are vital for diagnoses and estimates of global warming and climate change. Observations show that the World Ocean has warmed since the mid-1950 is [23] and modeling studies indicate that the detected warming is consistent with increases in greenhouse gases [24], [25] and [26]. This long-term trend was in reasonable agreement with model predictions, but the decadal variability was much larger in the observations. Sub-sampling of climate model output to match the actual data distribution results in large changes in the inferred temperature variability and reduces the discrepancy between models and observations [27]. In addition, historical data, including Mechanical Bathythermograph (MBTs) and Expendable Bathythermograph (XBTs), appear to have time-dependent biases that generate spurious decadal variability in the long-term record [28] and [29]. Correction of these biases, and the use of statistical techniques to compensate partially for sparse data coverage, appears to improve the records in the upper ocean. [30], using statistical techniques that allow for sparse data coverage and applying corrections to reduce systematic biases in the ocean temperature observations, report improved estimates of near-global ocean heat content and thermal expansion for the upper 300 m and 700 m. In the deep ocean, there are insufficient data in most regions to evaluate the veracity of the numerical models, although the limited data sets that do exist are beginning to be used to study variability over longer time-scales (e.g. [31]).

The actual rate of heat transport by the deep ocean, and hence the true status of the global ocean-atmosphere-land heat budget, remains unquantifiable due to the paucity of measurements. Most of the global ocean heat content estimates are limited to the upper 700 m; one exception is an estimate [23] that extends to 3000 m at pentadal resolution. This study suggests that the heat content of the deep ocean between 2000 and 3000 m is increasing, but it does not address changes in the abyssal layer below 3000 m. Repeat hydrographic measurements have recently been used to show that abyssal waters of Antarctic origin below 3000 m depth have warmed measurably in the last decade in the deep South Atlantic [32], North Pacific [33], South Pacific [31], South Indian oceans [14], and the Southern [34] oceans (Fig. 2).

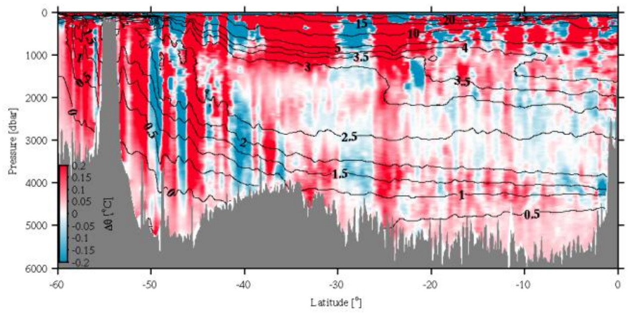

Figure 2. Differences in potential temperature, $\Delta\Theta$ [°C], in the western South Atlantic resulting from subtracting WOCE section A16 data taken in 1985 (and A23 in 1995 in the Scotia Sea, south of 54°S) from 2005 reoccupation data taken by the U.S. Climate Variability and Predictability (CLIVAR/CO_2) Repeat Hydrography Program. Values of $\Delta\Theta$ are color contoured (inset color bar) from –0.2°C to +0.2°C to accentuate deep changes. Mean theta is contoured (black lines) at 0.5°C intervals below 15°C, and 5°C intervals above 15°C. Abyssal warming in the Scotia Sea, Argentine Basin, and Brazil Basin reaches 0.04°C, equivalent to 0.5 W m-2 heating along the section to account for the warming at pressures exceeding 3000 dbar. After [32].

While the repeat hydrographic section data are useful in identifying signals requiring further study, once-a-decade sections cannot distinguish between true decadal variability and variability at shorter time-scales. Expansion of the existing observing system to quantitatively measure the ocean heat content below 2000 m on a more routine basis is critically needed in order to obtain a truly global estimate of ocean heat content and its relationship to climate change. Recommendations on how to expand the observing system to address this need will be presented in a subsequent section.

4. FRESH WATER BALANCE

The possibility that increased freshwater input to the high latitude ocean could cause a slowing of the thermohaline circulation, driving an abrupt change in climate, has attracted considerable interest [35]. Changes in upper ocean salinity have been observed in each of the ocean basins, with an increase in salinity in the subtropical evaporation zones and a decrease at higher latitudes that is consistent with a more vigorous hydrological cycle and increased supply of melt water at high latitudes [36]. Numerous studies have documented a freshening of North Atlantic Deep Water during nearly three decades from the mid-1960s to the mid-1990s, when the North Atlantic Oscillation (NAO) evolved to an extreme positive state (e.g. [1]). The freshening reversed in the mid-1990s. Weakening of westerlies associated with the NAO decline in the mid-1990s to mid-2000s caused a reduction of convection intensity in the Labrador Sea, a slowing and contraction of the subpolar gyre, and the northward advance of warm saline subtropical waters [37], [38], [39], [40] and [41]. Being rapidly transferred to deeper levels, the NAO-induced upper ocean changes led to increase in temperature and salinity of Labrador Sea Water (LSW) and the deep waters [42], [43] and [2]. Estimates based on data from the 60°N transatlantic section (Fig. 3a) show that the intermediate–deep water stratum became ~0.3°C warmer and 0.036 psu saltier in 1997–2006 [41]. The salinity increase (Fig. 3b) is comparable to the net magnitude of the preceding long-term freshening (~0.03 psu).

The 2006–1997 temperature and salinity differences at 60°N (Fig. 3) are positive through most of the water column. Zonally averaged differences on isopycnals (Fig. 3c) are also generally positive, indicating the ‘actual’ increase in temperature and salinity, i.e. not associated with isopycnal heaving. The maximum temperature and salinity increments (+0.5°C and +0.06 psu, respectively) are documented for the deep LSW core ($\sigma_0$27.78 kg/m^3) in the Irminger Sea. The distinct warming and salinification is also detected in the layer of shallow LSW (27.72–27.75 kg/m^3) and in the overflow-derived deep waters (σ_0> 27.80 kg/m^3).

While measurements are sparse in the Southern Ocean, several recent studies have detected changes in the salinity of Antarctic Bottom Water [44], [45], [46], [47], [48], [49] and [31]. The Ross Sea and Adélie Land regions supply about 40% of the total input of AABW [13]. Most of the AABW exported from both sources passes through the Australian Antarctic Basin, making it a good place to monitor changes in properties of the AABW formed in the Indian and Pacific sectors. The deep T-S relationship has changed throughout the basin in recent decades, with a shift toward fresher and lighter bottom water observed in the deepest 1000 m of the water column [49]. The freshening rate is comparable to that observed in the North Atlantic over the same time span, at comparable distances from the source regions. [50] and [46] suggest that the most likely source of the additional freshwater is basal melt of glacial ice in the Pacific sector. Enhanced basal melting there has been linked to warmer ocean temperatures [51]. In contrast, in the Weddell Sea the situation is ambiguous, with freshening of bottom water in the west [52] and an increase in the salinity of deep water in the east [34].

The evidence from the North Atlantic and the Southern Ocean suggests that the dense water sinking in both hemispheres is responding to changes in the high latitude freshwater balance, and is rapidly transmitting this climate signal to the deep ocean. However, in only a few places are the observations sufficiently frequent to avoid aliasing of interannual variability. Expanded arrays of continuous measurements of deep ocean properties are needed to better understand the MOC and its response to changes in forcing.

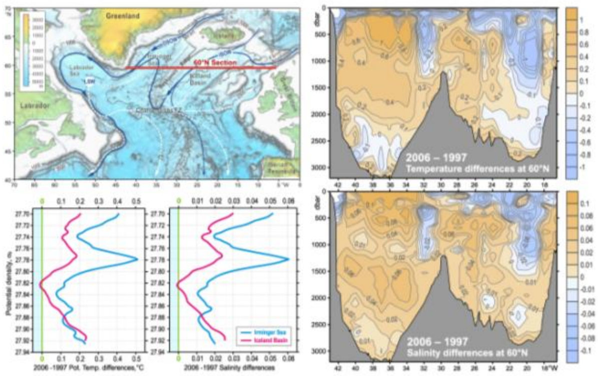

Figure 3: Upper left: Location of the 60°N section repeated annually by P. P. Shirshov Institute of Oceanology. Right: Temperature (°C) and salinity (psu) differences between 2006 and 1997. Lower left: Zonally averaged 2006–1997 potential temperature and salinity differences on isopycnals (σ_0) in the Irminger Sea (30–42°W) and Iceland Basin (16.5–30°W) at the LSW and deeper levels. Adapted from [42].

5. HE NEED FOR DEEP OCEAN CARBON OBSERVATIONS

The deep ocean accounts for more than half of the total (natural) oceanic carbon inventory. The deep ocean reservoir is unique compared to the upper ocean, as it exchanges on longer time-scales with the upper ocean compared with the exchanges between other reservoirs and sub-reservoirs [53]. As a result, it is believed that to date little of the anthropogenic atmospheric CO_2 from man's activities of consuming fossil fuels and land use changes has entered the deep ocean. The first data based estimates of anthropogenic CO_2 in the ocean suggest that less than 5% has penetrated deeper than 2000 m [4]. However, the separation of the anthropogenic CO_2 component from the total is based on empirical techniques [54]. These techniques either implicitly assume that the anthropogenic CO_2 is zero at depth, or they lack a robust means to determine it. Nevertheless, from recent high-quality observations, which were conducted under the framework of the CLIVAR/CO_2 Repeat Hydrography program, it is reported that signals of anthropogenic CO_2 were found in deep waters such us Circumpolar Deep Water in the South Pacific [55] and Antarctic Bottom Water in the South Atlantic [56], both of which are of Southern Ocean-origin. Within the measurement uncertainty of 2 µmol/kg-1 of total dissolved inorganic carbon (DIC), the deep ocean could contain as much as 17 Pg anthropogenic carbon, or about 14% of the current total estimated anthropogenic CO_2 inventory in the ocean.

Monitoring changes in the deep ocean carbon content is critical as the anthropogenic imprint is starting to penetrate deeper into the ocean. The penetration pathways are not a homogeneous diffusive invasion into the deeper waters, but rather are controlled by local conduits of rapid penetration and transport. In the deep ocean, observations of transient tracers (e.g., [57]) show that in certain regions, particularly the high latitudes, the exchanges between ocean and atmosphere are more rapid than previously thought. Moreover, decadal reoccupations of hydrographic transects in the global ocean indicate greater variation in biogeochemical parameters at depth, suggesting that natural and/or climate induced variability has a greater effect on deep waters then previously assumed [31].

Based on what is known about the penetration of anthropogenic carbon, and propagation of changes due to climate change, it appears that many of the changes in Dissolved Inorganic Carbon (DIC) will occur in areas with fragile deep-sea ecosystems, in particular deep ocean corals. They grow exceedingly slow and live at saturation states barely above the state of dissolution [58]. Small increases in CO_2 that will decrease the saturation state could have a detrimental effect on these organisms.

Due to the complexity of separating the small anthropogenic CO_2 imprint from the natural carbon cycle, particularly at depth, monitoring of other indicators of the anthropogenic imprint is desired. The transient tracers are critical in this respect. These include inert man-made compounds released by industrial activities such as a series of halogenated compounds such as chlorofluorocarbons CFC-11, CFC-12, and SF6 (e.g., [59] and [60]).

The CFCs and SF6 are unambiguous markers of waters that have been exposed to the atmosphere in the last 50 years. The CFCs were not produced in significant quantifies until the early 1950s, and have been curtailed since the late 1980s under the Montreal protocol, such that their release history differs from anthropogenic CO_2 (Fig. 4). Utilization of pairs of tracers and more advanced approaches such as the transit time distribution approach has increased the utility of CFC in quantifying the anthropogenic CO_2 input into the ocean (e.g. [61]).

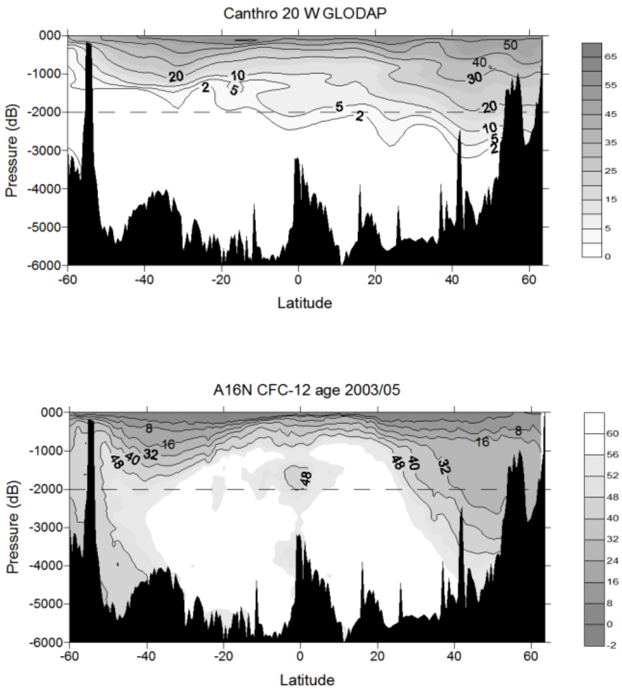

Figure 4 Top: Anthropogenic CO_2 levels along 20 ˚W in the Atlantic Ocean. The data are from the Global Ocean Data Analysis Project (GLODAP) synthesis product based on the World Ocean Circulation Experiment (WOCE) cruises in the 1990's, [62]. Bottom: Chlorofluorocarbon-12 (CFC-12) age section in the North Atlantic (nominally 20 ˚W) based on observations on the CLIVAR/CO_2 cruises A16N and A16S in 2003 and 2005, respectively [63]. The figures show the anthropogenic imprint penetrating to depths greater than 2000 m.

6. RECOMMENDATIONS FOR AN EXPANDED OBSERVING NETWORK

It is clear that to continue working towards understanding of climate variations and their impact on society, it is imperative to maintain existing observing systems while improving and expanding the deep ocean components of the Global Ocean Observing System. In what follows recommendations are provided for expanding the observing systems for deep circulation, for deep temperature and salinity variations (hence heat and fresh water estimates), and for deep observations of CO_2 and other chemical tracers. Recommendations are also provided in areas where technological advances are required to improve the ability to collect this data remotely using either free-floating or fixed observing platforms.

It is critical to monitor flow rates and properties of deep water (Tab. 1) at sites where upper ocean waters are injected into the deep ocean and where these waters are exchanged between sub-basins. The injection sites are the areas where new deep and bottom waters enter the global ocean circulation cell and it is important to monitor how the rates of deep-water injection and their properties are changing with time. The intra-basin exchange sites are regions where different deep-water masses separated by topographic features can mix and exchange properties. The highest priority sites are in the South Atlantic: the Weddell Sea, the Vema Channel and the Romanche Fracture Zone sill; in the South Pacific: the Ross Sea, the DWBC along the Kermadec Trench, and in the Samoan Passage in the North Atlantic: the Faroe Bank Channel, Denmark Straits, and Cape Farewell; and in the Indian Ocean: near the Adélie Land AABW source, in the DWBC along the edge of the Kerguelen Plateau, and possibly in choke points such as the Amirnate Passage and the entrance to the Perth Basin (see Fig. 5).

For circulation, ongoing and new observations should have three other foci: regions where topography significantly alters the deep circulation, choke points where deep water is exchanged between the major ocean basins (e.g. Drake Passage), and deep strong flows where the major water masses are carried significant distances within basins. The first priority is to maintain those deep ocean observations associated with any of these three foci that have been and are presently being collected to provide the longest possible climate time-scale records for study now.

This also includes global and regional repeat hydro-sections [64]; DWBC observations in the Atlantic using current meters, inverted echo sounders (IES/PIES/CPIES), and deep pressure gauges (i.e. 42°N, 39°N, 26.5°N, 16°N, and 34.5°S); choke point observations using similar moored instruments (Drake Passage, the GOOD HOPE line south of Africa, south of Australia); trans-basin arrays using mooring arrays (RAPID/MOCHA/WBTS); observations along the Antarctic continent (Weddell, Ross Seas and Adélie Land), and observations of northward flow of Antarctic Bottom Water into the South Atlantic, Pacific, and Indian oceans.

State Variable	Present Technology	Area of Interest
T, S	CTD/Rosette Argo floats, microcat PIES, Tomography	HS, FW, CO_2, DC
CO_2	CTD/Rosette	CO_2
Velocity	CMM, ADCP, PIES,HEFR, Argo & RAFOS floats Gliders	FW, DC
Oxygen	CTD/Rosette Moorings Argo and RAFOS floats	CO_2, DC
Additional variables		
Bottom pressure	Tide gauges, PIES, GRACE	DC
Nutrients	CTD/Rosette	CO_2
CFC, SF6	CTD/Rosette	CO_2, DC

Table 1: Summary of the sustainable state variables, which need to observed in the deep ocean. Areas of interest are HS= Heat Storage, FW= Fresh Water storage, CO_2 =CO_2 storage, DC = Deep circulation, CMM=current meter mooring, PIES=Pressure sensor equipped Inverted Echo Sounder.

Figure 5 illustrates specific key identified regions where either long-term records exist that should be maintained (blue diamonds), trans-basin sections exist that are already being occupied (blue lines) or should be initiated or completed (magenta lines), and two regions, the DWBC along the Kermadec Trench or through the Samoan Passage in the Pacific Ocean and along the Kerguelen Plateau in the Indian Ocean, where long-term DWBC records are not available but should be instituted (magenta stars). Satellites will be another valuable source of observations. Specifically, the *Gravity Recovery and Climate Experiment* (GRACE) satellite mission is presently being tested to provide information on the deep pressure field. Significant further validation is needed, and the expanded observing system being proposed herein will provide important assistance for this validation effort. Also, acoustic tomography may provide helpful data for temperature and salinity in the deep ocean. The role of acoustic tomography is discussed in a companion Community White Paper (CWP) [65].

For deep temperature and fresh water (salinity) observations, an important expansion of the observing system may be the development of deeper-reaching Argo floats and the expansion of the existing array using those floats (discussed in detail in another white paper in this volume [66]. The global nature of the Argo array is critical also for the observations of deep temperature and fresh water in order to properly understand the global integrated heat and fresh water content variability. Beyond the development of deeper reaching Argo floats, or of another technology that can provide a widely spaced grid of regular observations of temperature and salinity in the deep ocean, certain specific regions have been identified that are clearly in need of additional observations of temperature and salinity in the deep ocean. These areas are essentially the same as those identified for observations of choke-point, strong boundary current, and/or highly variable topography (high mixing regimes) circulation studies previously discussed (see Fig. 5). These observations should be made with the most efficient combinations of technology, including different types of moored instruments as needed and improved sensors (with low power draw, high stability, and resistance to biofouling).

Technology for routine deep ocean observations of carbon (e.g. via moored instruments) is not as far advanced as it is for velocity, temperature, and even salinity. The deep ocean carbon observing network design therefore must focus on sampling areas where we have strong evidence that significant changes will occur, and where the changes would have the largest impact. The WOCE Hydrographic Program (WOCE/WHP) of the 1990s repeat hydrography effort and the following CLIVAR/CO_2 programs provide an excellent observing scheme to assess qualitative changes in the deep ocean basin-wide on decadal timescales using repeat hydrographic surveys via ships. However, there are key areas that require higher frequency observations to better describe penetration pathways and mechanisms of transport to and within the deep ocean, as well as abyssal temperature and salinity variations. Carbon and transient tracer efforts are required for deep-water formation areas and areas of concentrated flow such as the DWBC. The key identified locations are illustrated in Fig. 5. The fate of deep ocean corals and the effects of ocean acidification are new research areas that need to be considered. Deep ocean corals are found on ocean margins around much of the world. Monitoring efforts of the impacts of increased CO_2 levels on these ecosystems should be coordinated with the ocean acidification observing programs (see [67]). In the longer term, an observing system to determine the pathways of anthropogenic CO_2 into the deep ocean, to quantify ocean acidification, and to quantify the amount that is penetrating will have similar design elements as the system to monitor changes in deep ocean heat content. The small anthropogenic CO_2 signal at depth also argues for several independent techniques to quantify the signal.

The mainstay of monitoring the deep ocean carbon system will be the aforementioned hydrographic surveys [64]. These surveys cover not only the deep waters but also the entire water column. In addition, there need to be hydrographic campaigns that include biogeochemical and transient tracer measurement targeting areas with rapid overturn and transport. Essentially this argues for observations at many of the key areas identified in the circulation discussion earlier, particularly in regions where longer records already exist (e.g. at 26.5°N in the North Atlantic). Ultimately, to quantify deep storage of heat, freshwater and carbon, a global temporally and spatially resolved observing system for the sub-Argo ocean will be required.

In addition to maintaining these critical velocity, heat, salt, and carbon systems and improving their capability to collect data on climate time-scales, new improvements in the observing system are required. Specifically, in addition to the development of deeper-reaching Argo floats and other systems mentioned earlier, there is a critical need for the development of cost effective systems for retrieving data from deep moored instruments that can provide new information about deep ocean variability. Ideally these deep moored systems would be used for providing data for long periods of time (up to 4 to 5 years) without the need or the use of a ship, and in near real time-scales (3 to 6 months).

Several different technologies for the remote retrieval of data from deep moored instruments are presently being developed around the globe or are proposed to be developed (e.g., CWP by [66], [65], [68], [69], [70] and [71]. The Woods Hole Oceanographic Institution system called “UltraMoor” is perhaps the furthest along, having been used in several deployments off the eastern seaboard of the United States.

A second system, developed by the German company Optimare in consultation with the Alfred Wegener Institute and the University of Kiel, involves a set of up to four glass spheres that can be connected through an infrared optical link to a moored IES/PIES/CPIES. A third example, not currently developed for deep ocean measurements, uses the PICO moored technology developed by Pacific Marine Environmental Laboratory, with "line crawlers" that move up and down the mooring cable taking measurements [72].

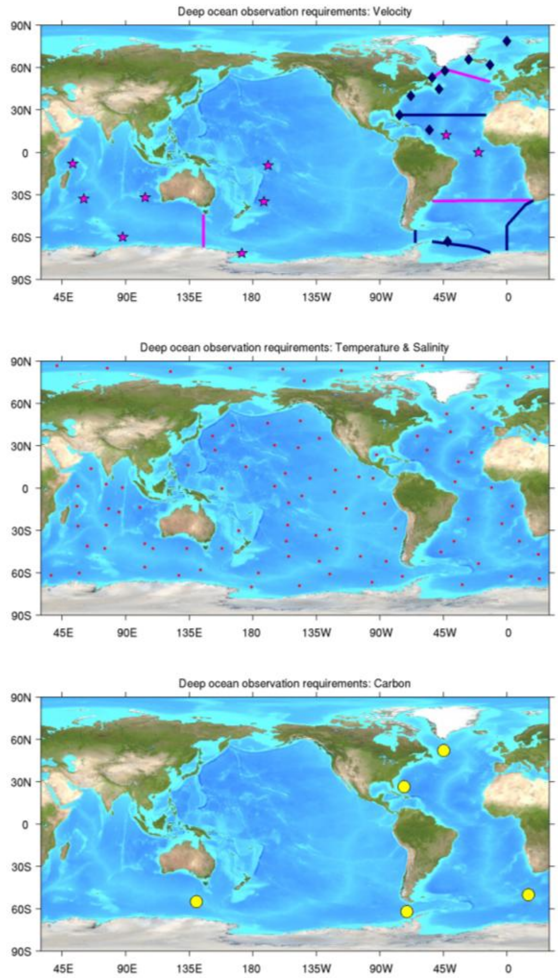

Figure 5: Recommended locations for either maintaining or expanding the observing system in the deep ocean. Top panel: Recommendations for deep ocean velocity that must be maintained (blue) or should be improved/completed or initiated (magenta). Diamonds and stars indicate key regions for focused observing arrays, while lines indicate regions where basin-wide moored instrument lines are recommended. Middle panel: Idealized recommendation for a network of sites where deep temperature and salinity observations should be collected. A denser array of T and S measurements are envisioned at the locations of the deep circulation sites. The actual number of measurements required to quantify global changes in heat and freshwater storage may be more than indicated in this schematic. Bottom panel: Recommendations for locations where routine observations of deep carbon should be improved or initiated. Note that for all three panels these recommendations are in addition to the maintenance of the repeat hydrographic program (see [64]).

A final example of development in this area is a system of data pods that will be connected via a short distance radio-frequency communication system that can be connected to an IES/PIES/CPIES, a bottom mounted Acoustic Doppler Current Profiler, or nearly any other type of system that can be internally powered and can output data via a serial cable during operation. This system, under development at the Atlantic Oceanographic and Meteorological Laboratory, is envisioned to include as many as 18 data pods, which would allow for quarterly satellite data transmissions over a five-year deployment. For both of the latter two systems, the addition of temperature sensors to the pop-up instrument might result in a significant improvement of the estimates of heat content along the whole water column. Support for the development of these types of data delivery systems will be critical for the expansion of the observing system to improve deep ocean observations, particularly in remote regions where ship visits are infrequent.

Beyond the modification of existing systems to collect data over a larger range of depths (e.g. deeper Argo floats, deep gliders, etc.) and systems to collect data remotely from existing mooring technologies, completely new instruments and techniques will be needed to provide the necessary advances in deep ocean understanding (also discussed in companion CWP, (e.g. [66], [69], [71] and [70]. An example of a new instrument presently under development that would improve circulation studies is a program presently underway at the Universities of Washington and Hawaii to merge the existing technologies of a pressure-equipped inverted echo sounder with that of a horizontal electric field recorder to create an HPIES. Similar new systems must be developed and deployed throughout the deep global ocean to provide the data necessary to further climate science and knowledge. This includes long-lived moored salinity sensors, deep moored oxygen sensors, and mooring-capable carbon/biogeochemical monitoring systems.

In general improved autonomous duration of sensors (low power draw, stability to drift, and resistance to biofouling) is needed. Another possible instrument would be an expendable device built to measure near-bottom temperature for several years before rising to the surface to telemeter the collected data. This instrument would allow increased spatial and temporal resolution of changes in bottom temperature compared with infrequent and widely separated repeat hydrographic sections

7. STANDARDS AND BENEFITS

Given the sparseness of abyssal data, models will be needed to further interpret deep ocean observations. As suggested in companion CWP [73], [71] it would be of value to the community to create a centralized model output distribution center that will distribute the model and reanalysis products as soon as they became available.

Standards for measurements accuracy and precision should be established and determined by the scientific community based on the signals to be measured. As described in this paper, the development of new cost effective instruments to obtain the required observations implies that these new developments may change the required standard of measurements. The development of autonomous instruments (e.g. deep ocean moorings that will release data at climate time scale intervals) will considerably reduce the cost of the observing system by reducing the need of ship time operations.

The expansion of the observing system towards the deep ocean will require that new standards be developed for metadata and data distribution. Digital availability of the entire records in a format suitable for use by the research and operational communities should be made a priority. Real and near-real time data should be free and available to the scientific community upon collection through the distribution data centers (e.g. Global Telecommunication System, GTS). An archive of metadata for all in situ observations should be filled by those collecting data from the proposed observing system as soon as possible with information on both current and historical deployments. The quality control procedures, type of instruments, calibration procedures and coefficients used, are critical parameters to be included in the metadata, which is essential for intercomparison with data independent platforms (e.g. VOS, buoys, research vessels, and satellites), to allow independent validation and homogenization of records.

The main users of the data will be the scientific community, who use the data for studies of the ocean and its relation to climate, and the operational centers, which will assimilate the data collected and quality controlled into their operational prediction models and reanalysis. Improvement of these models will help agricultural planning, urban planning, economic development, and ecosystem based management.

The formation of a Scientific Steering Team (SST) is recommended. The SST will determine the standards for data collection, its distribution and will periodically evaluate the compliance with these standards. This will allow to assess the status of the implementation of this component of the observing system, and to discuss its contributions to the scientific and operational communities.

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