FUTURE OBSERVATIONS FOR MONITORING GLOBAL OCEAN HEAT CONTENT

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ABSTRACT

This community white paper outlines the requirements of the future observing system necessary for measuring and advancing understanding of global ocean heat uptake and heat content variability, with an emphasis on the *in situ* observing system. We review the progress made in observation-based estimates of ocean heat uptake since Ocean Obs'99 and propose a future observational strategy.

Some of the key scientific questions addressed are:

1. What future observations are required to monitor global ocean heat content?
2. How has new technology improved our ability to make estimates of ocean heat uptake?
3. What are the current estimates of global and regional ocean heat uptake and what are the uncertainties?
4. What is the impact of instrumental biases and gridding methodology on estimates of ocean heat uptake?

1. SUMMARY

- Since Ocean Obs'99, the gradual development of the Argo array of profiling floats has dramatically improved our ability to make estimates of ocean heat uptake and monitor global ocean heat content in the upper 2000 m of the water column. The improved sampling and coverage under Argo post-2006 has allowed estimates of the annual average heat content in the upper ocean that are largely insensitive to in-filling assumptions. However, prior to Argo the *in situ* record is spatially inhomogeneous and mostly limited to the upper few hundred meters, which limits our understanding of the deeper ocean heat content change.
- Recent research has highlighted systematic data errors, particularly with depths estimated for expendable bathythermographs (XBTs) and pressure measured directly by Argo float sensors. Work is currently underway to investigate these problems and to develop and refine the necessary corrections. This is a priority research activity for the ocean observations community
- In order to close the energy budget of the Earth"s climate we must move to an observing system capable of measuring the global ocean in its entirety. Despite the improved data coverage associated with Argo, the deep (> 2000 m) and ice-covered ocean remain largely un-observed. Currently, the only full-depth ocean observations come from the dedicated hydrographic cruises, which can only sample a very small area of the deep ocean. **In the future, these hydrographic cruises must be augmented by an array of deep floats, moored instruments, gliders, or a combination thereof to allow a true global integral of ocean heat content from the surface to the sea floor.**
- To understand better the impacts of future climate change, the emphasis of scientific research into ocean heat uptake must necessarily switch to regional scales. This change of focus will impose even more demanding requirements on the observing array. It also places a requirement to observe or accurately model/predict the regional redistribution of heat content due to ocean advection. The synergy between satellite altimeter and gravity measurements and Argo observations must continue to be exploited in order to achieve the most complete understanding of the observed changes.

2. WHY IS OCEAN HEAT CONTENT IMPORTANT?

It has been estimated that over the latter half of the 20th century, more than 80% of the energy gained by the Earth"s climate system as a result of anthropogenic forcing has accumulated in the subsurface ocean [1]. If we are to achieve an observing system capable of monitoring the Earth"s radiation balance [2] and [3], it is essential that we can fully and accurately quantify changes in both regional and global ocean heat content over the full ocean depth. Upper ocean (0-700 m) heat content changes have been estimated from a vast number of historical observations [4-6]. For future climate change, the rate of ocean heat uptake is of primary importance, since it acts to postpone the surface temperature rise and provides a powerful observational constraint on climate model projections [7-9]. Ocean heat uptake also provides a measure of the total radiative forcing of the climate system [10] and [11]. In addition, expansion of seawater associated with ocean warming is an important contribution to sea-level rise [4] and [12-14]. Observation-based estimates of ocean heat uptake provide an important measure of energy gained by the climate system and a fundamental baseline for the evaluation of climate-change model simulations [15-17].

3. PROGRESS SINCE OCEAN OBS'99

The Ocean Obs'99 conference took place as the observational phase of the World Ocean Circulation Experiment (WOCE) was drawing to a close. WOCE was the first systematic attempt to measure the global ocean to full-depth by occupying a large number of hydrographic sections between 1990 and 1998. The aims of the WOCE program were to establish the role of the oceans in the earth's climate and to obtain a baseline

dataset against which future change could be assessed.

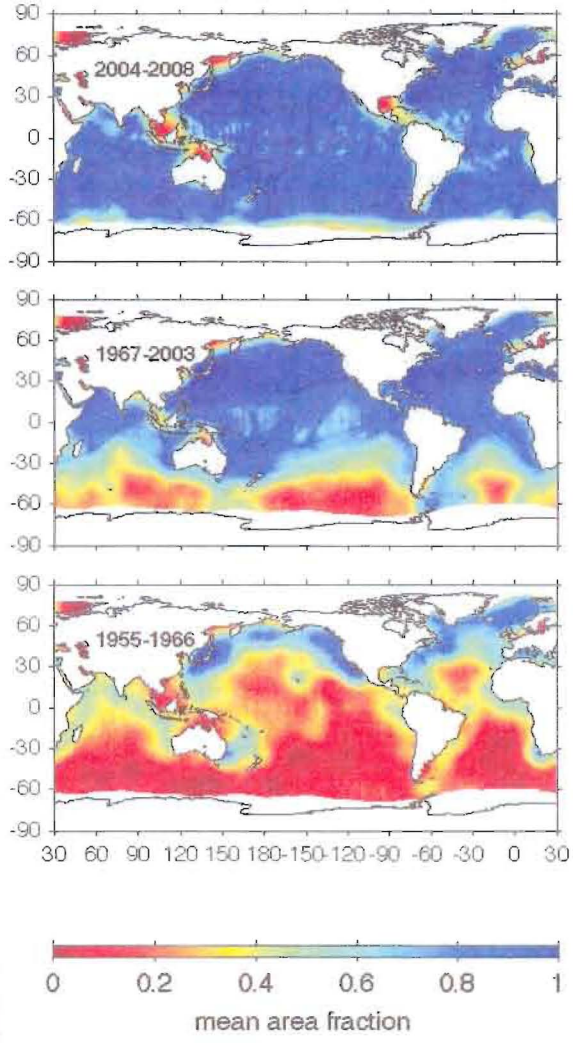

Figure 1: Mean of annual "observed" area coverage for the upper 750 m from 2004 to 2008 (top panel), 1967 to 2003 (middle panel) and 1955-1966 (bottom panel) updated from Lyman and Johnson (2008). The mapping used is a simple objective map containing both a small-scale (~100 km) and a large-scale (~1000 km) in its covariance function.

3.1 Improved *in situ* observational coverage

The early 2000s saw the introduction of a large number of autonomous profiling floats as part of the Argo observing array [19] (http://www.argo.ucsd.edu/). There are currently over 3000 Argo floats throughout the global ocean, drifting at depth and surfacing periodically to transmit data via the global telecommunications system. A typical float measures temperature and salinity (salt content) to a depth of about 2000 m and transmits the data every 10 days. The Argo array has revolutionized our ability to observe the subsurface ocean and makes up the vast majority of present-day subsurface temperature and salinity measurements [20].

Annual mean sampling to a depth of 750 m (Fig. 1), which is the maximum depth range of most XBTs but represents only about 20% of the full-depth of the open ocean, has vastly improved after the spin-up of the Argo observing array for the period 2004-2008. Note, however, that large areas at high latitudes remain poorly sampled and that even the Argo sampling depth of approximately 2000 m represents only the upper 50% of the average open ocean depth.

3.2 Discovery and correction of observational biases

Around the time of publication of the IPCC 4th assessment, results were published showing evidence of a time-varying warm bias in expendable bathythermograph (XBT) observations [21]. These instruments were introduced in the late 1960s and constitute over 50% of the observed temperature profiles between the early 1970s and the late 1990s [22]. Correction of the time-varying warm bias, using a number of different approaches [5], [6] and [22] results in a dramatic reduction of the interdecadal variability in ocean heat content and, initial results suggest, a more favorable comparison with climate modeling efforts [4].

Some systematic errors in pressure were also identified in a small population of Argo floats [23]. Although floats with large (>20 db) pressure errors have now been identified and flagged, efforts to calibrate the entire array to a globally averaged pressure error of approximately 1 db (~ 5 mm of globally averaged thermosteric sea level or 3 × 1022 J of ocean heat content) are still ongoing (http://www.argo-ucsd.edu/) and will require continuous monitoring into the future. Sea surface height data from satellite altimeters has also proven extremely valuable in rapidly identifying systematic errors in XBT and Argo data [24]. However, shipboard research-quality CTD (Conductivity-Temperature-Depth) data remain the gold standard for such global calibration efforts and our ability to maintain the desired accuracy of ocean heat content estimates is contingent upon having a robust program for collecting CTD data and making it readily available to the entire scientific community.

3.3 Satellite-based estimates of ocean heat uptake

At the time of Ocean Obs'99, satellite altimeter measurements of sea surface height were well-established and making routine measurements of global and regional sea level. With the use of GRACE ("Gravity Recovery and Climate Experiment") satellites, launched in March 2004, we are now able to separate out the sea level changes associated with ocean

heat content. The gravity measurements constrain ocean mass changes (from e.g. melting ice, changes in land water storage), the satellite altimetry provides accurate measurements of ocean volume changes and the thermal expansion component can be estimated from the residual, see [25] for further details. These independent measurements provide a full-depth estimate of changes in ocean heat content and are invaluable for cross-validation with the *in situ* observations, so that we can evaluate the "health" of the observing system.

3.4 Acoustic thermometry

Since the Ocean Obs'99 conference, there has been a decade of basin-scale acoustic thermometry measurements in the North Pacific Ocean [26] and [27]. These methods have a number of attractive properties [27] and [28]. They are inherently spatially averaging, suppressing the effects of mesoscale variability and directly providing measures of depth-integrated temperature that extend into the deep (> 2000 m) ocean. They provide high temporal resolution and can be made without risk of calibration drift, as they depend only on the accurate measurement of time. They can also be used in ice-covered regions. As such, they present many complimentary properties to the *in situ* observing array, for which mesoscale variability, temporal resolution, calibration drift and sampling of ice-covered regions present major limitations.

3.5 Detection of an anthropogenic influence on climate

The subsurface ocean temperature is shaped by both "external" climate forcings (e.g. changes in greenhouse gases, aerosols, solar variations) and the inherent, unforced "internal" variability associated with the climate system. Another important development since Ocean Obs'99 has been the use of these observations as a key database for detection and attribution of anthropogenic influence [15], [16] and [29]. The IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report (AR4) [30] noted that climate model simulations failed to reproduce the same level of inter-decadal variability in ocean heat uptake as the observations. As a result, confidence in the attribution of climate change was reduced, and noted as a key uncertainty in the AR4 technical summary [31]:

"Despite improved understanding, uncertainties in the model-simulated internal climate variability limit some aspects of attribution studies. For example, there are apparent discrepancies between estimates of ocean heat content variability from models and observations."

This discrepancy has now been found to be largely an artefact of biases in the observations [4], [21] and [22]. Reference [32] has recently used the novel approach of estimating ocean temperature changes relative to a fixed isotherm, which they show to be immune to one major source of XBT bias, due to fall rates. They also show an improved signal-to-noise ratio in estimating observational temperature trends and are able to detect both anthropogenic and natural (volcanic) influences in historical ocean temperatures over the upper few hundred meters. This new application of ocean heat content for validating climate models makes it all the more critical to calibrate past and present observational systems.

3.6 Ocean state estimation

Ocean state estimation has also emerged as an important tool to study ocean climate and climate variability, by combining the vast array of ocean observations in a dynamically consistent framework using general circulation models. Since these global syntheses provide a full description of the time varying ocean state, they can be used to estimate changes in ocean heat content [33] and [34]. Ocean state estimates also provide a means for assessing the observational requirements for improving our understanding of ocean climate [35]. For further information, we refer the reader to the following Ocean Obs,,09 Community White Papers [34-37].

3.7 Current estimates of global ocean heat uptake

Figure 2 shows recent estimates of ocean heat content (OHC) changes for the 0-700 m layer from a number of different research groups. The 1992-2002 mean, when all the products overlap, was removed to allow the trends to be compared. The spread of the analyses could represent a measure of the "structural" uncertainty in the calculation methods, analogous to an ensemble of model runs. These estimates are effectively an update of Fig. 5.1 in the IPCC AR4 [30]. The analyses vary in their input data; quality control procedures; gridding and infilling methodology (the assumptions made in areas of missing data), bias corrections and choice of reference climatology. These differences are explored further in Sect. 6.

Many of the time series show similar low frequency signals (i.e. the basic shape of the curve), but there are differences in the both the estimated interannual variability and long-term trends. Differences in the earlier, data-sparse years are most sensitive to different infilling methodologies. However, there are also substantial differences over the latter half of the time series. It is of great importance that we work to understand and account for the differences among the data sets, in order that the observations are used appropriately to better understand the climate system and validate climate models.

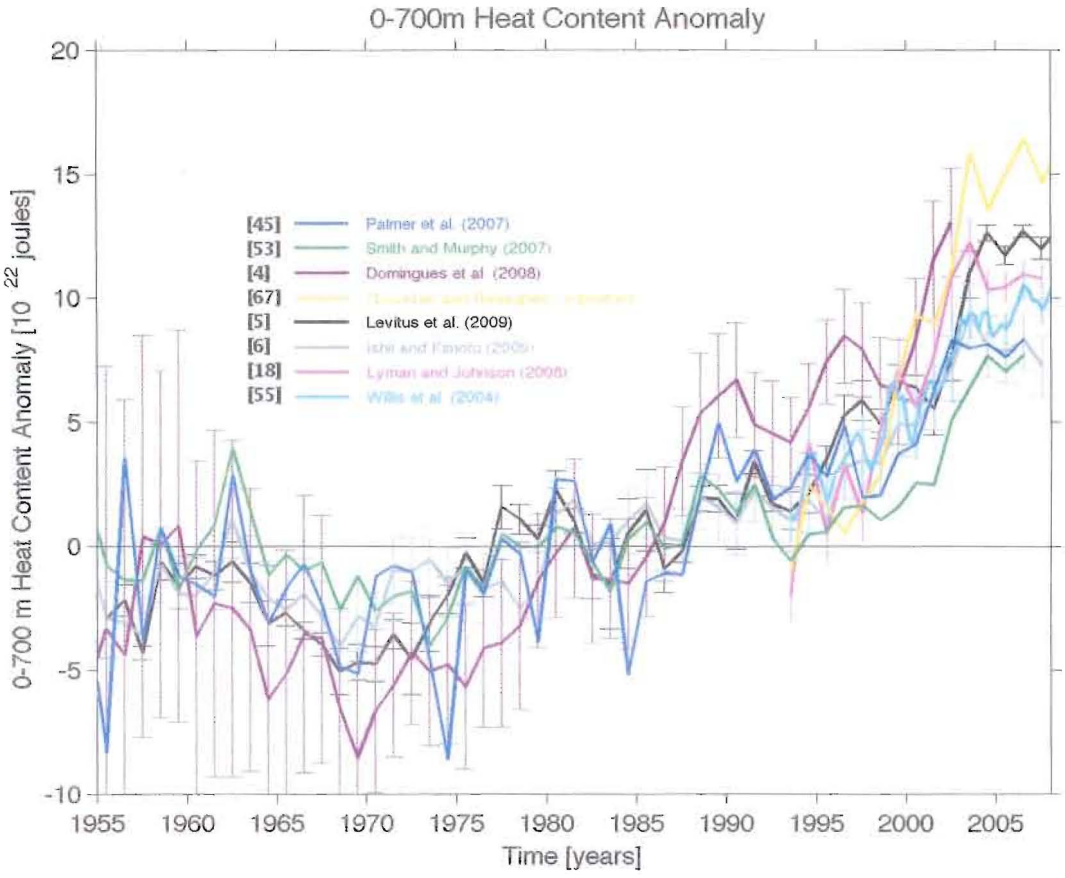

Figure 2: A number of observation-based estimates of annual ocean heat content anomaly (1022 J) for the 0-700 m layer. Differences among the time series arise from: input data; quality control procedure; gridding and infilling methodology (what assumptions are made in areas of missing data); bias correction methodology; and choice of reference climatology. Anomalies are computed relative to the 1955-2002 average.

Comparisons of hydrographic observations made during CLIVAR (Climate Variability and Predictability), repeating WOCE sections, reveal interesting changes below the 700 m depth limit. For instance, bottom waters of Antarctic origin in the deep South Atlantic [38], Pacific [39-41], and South Indian Oceans [42] have all warmed over the last decade. Analyses of the Argo observations compared to the historical data also reveal substantial temperature changes through the upper 2000 m [43].

These new studies complement previous results [1] and [44], indicating significant warming between 700 and 3000 m in the North Atlantic Ocean. Such abyssal and deep changes appear to make a substantial contribution to rising ocean heat content and hence sea level changes [4].

4. SPATIAL PATTERNS OF OCEAN HEAT CONTENT CHANGE

The oceans do not warm up uniformly, for example the Atlantic has made the largest contribution to upper ocean heat uptake over the last 50 years or so [1], [45] and [46]. While improving understanding of global integrated ocean heat uptake (Fig. 2) is of enormous scientific importance, ultimately the effects of climate change, e.g. sea level rise, are felt at the regional level. Therefore, we must develop more understanding of regional changes and the spatial patterns of ocean warming.

The warming trends in the 0-700 m layer from the three global analyses for the period 1970-2000 (Fig. 3a-c) show similar patterns and magnitudes in the relatively well-observed Northern Hemisphere. The qualitative agreement between the Levitus et al. (2009) [5] and Ishii and Kimoto (2009) [6] analyses is

remarkable, even in the data sparse Southern Ocean, in which the majority of 2°×2° grid boxes of the Palmer [45] et al. (2007) analysis have less than 10 sampled years over the 1970-2000 period (Fig 3c). However, recent work suggests that the infilling methodologies of Levitus et al. (2009) [5] and Ishii and Kimoto (2009) [6] may underestimate the trends in these poorly observed regions [18] and [47].

Preliminary investigations using one set of XBT corrections [22] suggest that spatial warming patterns are not sensitive to whether these corrections are applied [Palmer pers. comm.]. This is probably because the local trends are an order of magnitude larger than the globally-integrated trends, and most corrections are a function only of time and depth [5], [6] and [22] For example, the heat content time series shown previously (Fig. 2) have long-term trends equivalent to approximately 0.02-0.03°C per decade (c.f. Fig 3).

The Gille (2008) [47] analysis (Fig. 3d) uses a different method that is designed to cope with sparse observations. Values are computed by determining trends for matched pairs of observations, collected within 220 km of each other and separated in time by at least 10 years. The trends are then averaged up into 5°×5° latitude-longitude bins using data over the period 1970-2000. There are large differences between the Gille analysis (Fig. 3d) and the Levitus and Ishii and Kimoto analyses (Fig. 3a, b). We note that the averaging strategy used in the Gille analysis probably weights different time periods preferentially. The drastically improved sampling and coverage from Argo in the Southern Ocean will enable much more robust estimates of ocean warming in this region.

Spatial patterns of ocean heat uptake are extremely sensitive to the trend period chosen [45 and [48]. This sensitivity arises because the phase of the climate modes (such ENSO (El Niño/Southern Oscillation)), that represent the internal "random" variability of the climate system, can have a large regional impact. Reference [49], for example, demonstrates that the heat content changes associated with the North Atlantic Oscillation dominate the spatial pattern of heat content changes in the North Atlantic Ocean from 1950 to 2000. This work and others [50] demonstrate that the local heat content is modulated both by changes in ocean circulation and air-sea heat fluxes associated with the time-evolution of these modes. It is imperative that we have an observing system that enables us to understand the observed changes in ocean heat content from a mechanistic point of view [46] and [49-51]. *In situ* measurements of both temperature and salinity are essential to separate and understand ocean heat content changes arising from thermodynamic processes (e.g. changes in air-sea heat flux) from ocean dynamical processes (e.g. changes in ocean circulation).

5. WHERE DO DIFFERENCES IN ESTIMATES OF OCEAN HEAT UPTAKE COME FROM?

In this section, we briefly describe the factors that can contribute to differences among the analyses presented in Figs. 2 and 3.

5.1 Input data and quality control

5.2 The starting point for any analysis of ocean heat content change is the observational database used. The observations will impact the data coverage and homogeneity. Reference [4], for example, decided to exclude mechanical bathythermograph (MBT) observations for reasons of data quality. Quality control (QC) procedures are designed to remove erroneous/suspect data from the analyses. QC usually follows a series of checks that can be performed automatically, manually or some combination of the two. Common checks are for "gross errors" (temperatures unrealistically high/low) and a simple "statistical check" (data at a particular location lies outside some expected range).

5.3 Infilling assumptions

Given the poor historical observational coverage (Fig. 1), the assumptions made in areas of missing data, i.e. what value to assign, can have a big impact on estimates of OHC trend and variability [18] and [47]. Such assumptions include taking average value of the sampled area to representative of the integral [45]; using optimal interpolation that damps to a zero anomaly on some space and/or timescale [1] and [52]; estimating the modes of variability (EOFs) from a well-observed period and using these to assist the infilling of missing data areas [4]; or estimating covariances from a climate model or the observations themselves [53, Smith pers. comm.].

5.4 Correction of data biases

Biases found recently in XBT and MBT data can significantly distort the global time series of the OHC. Thus, a local maximum on the time series by [1] and [52] around 1975-1980 was found to be an artefact due to a time-varying warm bias in the XBT data [21] and [22]. Subsequently, a number of groups have developed bias corrections for expendable bathythermographs (XBTs), which vary in methodology and underlying assumptions. To illustrate the differences, new versions of the EN3 dataset [54]

were created with the various bias corrections applied. Global annual temperature anomalies relative to 1971-2000 for the 0-700 m layer were calculated for each version (Fig. 4) following the methodology of [45]. All instrument types (Argo, XBTs, MBTs, etc.) were included. Since the time series were calculated from the same quality controlled data, the same climatology and using the same processing methodology, the differences that are seen are related to the XBT corrections and the varying ways in which they are defined. For example, a fundamental problem with XBT data is a lack of accurate metadata, with approximately half of XBTs being of unknown type [6]. This issue is handled differently for each set of XBT corrections and this introduces additional uncertainty in the corrections. This exercise demonstrates the need for good quality metadata to be kept with all observations, in order to avoid confusion. It is possible that through an international effort some of the missing XBT metadata could be recovered and used to reduce uncertainties in XBT corrections.

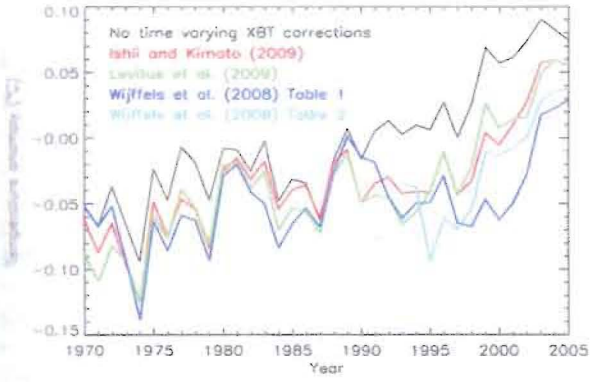

Figure 4: Global average temperature anomalies relative to 1971-2000 climatology with no XBT corrections applied for the 0-700 m layer calculated using the same data and processing methodologies but using different XBT bias corrections.

5.5 Choice of climatology

The historically uneven ocean sampling means that OHC time series are computed as anomalies relative to some reference climatology. This step can help to avoid aliasing of the seasonal cycle into the resulting analyses. However, both the resolution and the temporal sampling of the reference climatology can influence the estimated OHC changes. The asymmetry in average sampling year between the Northern and Southern Hemisphere (Fig. 5) could lead to underestimated rates of ocean warming, unless this is accounted for [4] and [22].

6. FUTURE PLANS

In this section we highlight the key challenges for improving our understanding of ocean heat content changes and future development of our monitoring capability.

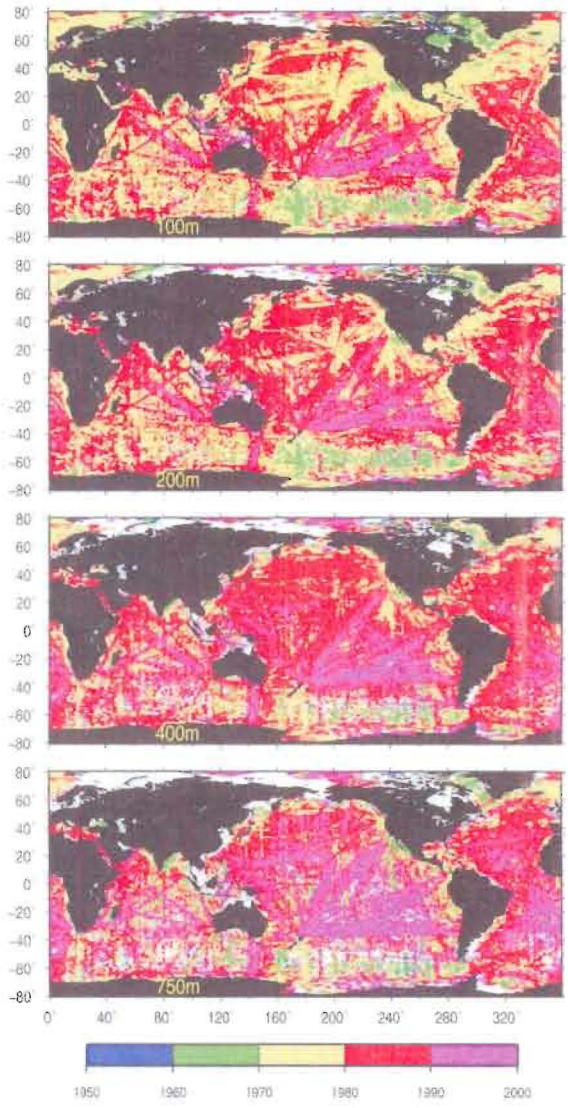

Figure 5: The average sampling year of all observations in 111km × 111km grid boxes, for the World Ocean Database 2005. Profiling float data are not included in the analysis.

6.1 Maintaining the existing observing array

The number one priority is to sustain the Argo array of profiling floats and the satellite altimeter and gravity capability.

6.2 Maintaining the existing observing array

The number one priority is to sustain the Argo array of profiling floats and the satellite altimeter and gravity measurements. The Argo data are fundamental to a mechanistic understanding of ocean heat content change, since they provide the temperature and salinity

observations necessary to separate changes arising from thermodynamic (diabatic) and dynamic (adiabatic) processes. While satellite products can provide information on the column-integrated sea-level and global ocean heat uptake, it is Argo that will facilitate understanding of the vertical structure and spatial patterns of ocean heat uptake and sea-level change. Altimeter data provide higher temporal frequency monitoring of circulation and can be used for *in situ* QC [24], or infilling [55], or characterizing modes of variability [4]. It is important that consecutive satellite missions have sufficient overlap for inter-calibration [56].

6.3 Improving the coverage of the *in situ* observations

There are still large regions of the upper ocean that are historically under-sampled (Fig. 1) [18] and [57], which makes annual heat content analyses problematic. This irregular sampling could lead to an underestimation of the global trend by up to 70% using 1955 to 1966 sampling, or nearly 30% using 1967 to 2003 sampling, depending on infill technique [18]. Currently the Argo array provides adequate coverage to estimate annual global heat content in the ice-free upper ocean. However, if upper ocean heat content estimates are pushed to resolve monthly timescales and smaller regional scales, then the error due to irregular sampling becomes increasingly important. Deep and ice covered waters remain highly under-sampled, largely due to the technological challenges of making observations in these regions. In regions of partial ice cover, marine mammal observations [58] could play an important role in development of the observing system. Autonomous float technologies are currently being developed that could expand the coverage of Argo into the ice-covered ocean [59]. The use of acoustic thermometry in ice-covered regions could also be explored further [28].

The deep ocean accounts for a significant fraction of the global energy imbalance [1] and [41]. Reference [41] estimated that the deep ocean could add an additional 2-10% to the upper ocean heat content trend, which is likely to grow in importance as the anthropogenic warming signal propagates to increasing depth with time. Temperature measurements in the abyss, ventilated by deep and bottom water formation, are currently only measured globally by repeat hydrographic sections, which are too widely separated in space and time for accurate heat budget integrals. Hydrography should therefore be augmented by an array of deep floats, moored instruments, gliders, or a combination thereof to allow a truly global integral of ocean heat content from the surface to the sea floor. It will take some time to develop such a system and determine the optimum mix of measurements given the technical challenges. Deep moorings at known "choke-points", where inter-basin deep-water inflow/outflows can have a large associated heat transport [60] would also help to monitor the deep ocean heat content.

The coastal ocean and marginal seas were not included in the Argo core mission [59], but represent a substantial area of the global ocean. In order to fully quantify the rate of ocean heat uptake it is important that sampling of these regions is improved. We support initiatives such as the MedArgo (Mediterranean & Black Sea Argo Centre program, in realizing this goal [61], but recommend that such efforts are coordinated internationally. Reference [62] outlines a strategic action plan for implementing the coastal module of the Global Ocean Observing System. It could be advantageous if these efforts were integrated with the global module.

6.4 Calibration, quality control and timeliness of data

In addition to expanding coverage and improving sampling, a system must be established for calibrating the global networks of XBT and Argo observations to the accuracy required for the study of global ocean heat content: 1db accuracy in pressure or depth, 0.01 °C in temperature, and 0.01 PSS-78 PSU in salinity* (Tab. 1). Such a system will require an ongoing and systematic program of continued high-quality hydrographic observations such as those collected during WOCE. In order to meet the goal of ongoing monitoring of global ocean heat content, these calibration data should be available in near real-time, internationally without restriction, and be permanently archived at ocean data centers. The expansion of acoustic thermometry observations [28] into all major ocean basins could provide very valuable monitoring in its own right as well as additional calibration data. The potential utility of acoustic thermometry for XBT calibration should be explored using the existing Pacific data. Detailed meta-data for all future observations are an important consideration when making improvements to the observing system. The problems that can arise from data in homogeneity and inadequate meta-data are discussed by [56].

Rigorous QC of the observations is essential for all downstream climate applications – whether it be monitoring, forecast initialization or historical analyses and reanalyses. More resources need to be put into inter-comparison of QC procedures. Greater international collaboration in this area could yield higher quality data

* Note that an 0.01 PSS-78 salinity change is roughly equivalent to an 0.04°C temp change, in terms of density change (hence sea-level) but one cannot know salinity to better than 0.01 PSS-78 unless temperature is known to 0.01°C.

sets for climate research. For example, scientists at CSIRO (Commonwealth Scientific and Industrial Research Organisation) have proposed a "clean up" of the historical XBT record through international collaboration, using the QuOTA system (Royal Navy) [63].

One of the key challenges for monitoring of ocean heat content is the time lag associated with carrying out rigorous QC and calibration of the observations, particularly when manual quality control procedures are required. It is not yet clear to what extent a "climate quality" QC system can be automated. Currently, there is approximately a 12-month delay before the Argo "delayed mode" data become available, due largely to the need to correct data manually and the need to assess quality of profiles with relatively long time-series. Since there are a number of different groups carrying out the delayed mode QC, there is also the potential problem of systematic biases between float batches. Therefore, an internationally agreed system for QC of data suitable for monitoring of ocean heat content should be considered.

6.5 Accuracy requirements for the global array

The accuracy requirements for monitoring of ocean heat content depend on the scientific application, however there is a clear need to move beyond detection of the secular, large-scale anthropogenic warming [15] and [16] towards understanding changes on regional scales and sub-annual time scales (e.g. volcanic responses, regional phenomena such as ENSO). This regional focus is essential to develop and test climate models that are suitable for making the regional predictions needed for then assessing socio-economic impacts of future climate change. As one moves to regional scales, sampling uncertainties can increase dramatically. Reference [64] has estimated sampling uncertainty of the 0-220 m layer temperature for a number of different ocean basins. Their results suggest that even for the more recent decades, the sampling uncertainty for the Atlantic and Indian Oceans can exceed the global uncertainty by a factor of two. However, more work needs to be carried out to better understand the sampling requirements for regional climate applications.

A fundamental scientific challenge is closure of the Earth"s radiation budget, for which the observed ocean heat content provides a powerful constraint [1]. The interannual variability in net radiation has been recently estimated as ± 0.7 W m-2 [11]. Reference [18] estimates the current (2006 Argo coverage) *in situ* sampling uncertainty for the 0-700 m layer is approximately ± 0.4 Wm-2 over multi-year time scales at the 95% level. The authors also demonstrate the important property that, post-2006, the estimated sampling error is insensitive to the choice of infilling assumptions. Therefore, the present observing array must be sustained as a minimum requirement, in order that we can resolve interannual changes in Earth"s radiation balance and provide useful cross-validation with satellite estimates [11].

It is clear that observing system experiments [65] and ocean state estimates [34-37] will have an important role to play in informing the accuracy requirements and deployment of future observations of ocean heat content. Ocean state estimates provide a dynamically consistent framework for combining *in situ* and remotely sensed observations, which will aid our mechanistic understanding of ocean heat content changes. We note that observing system experiments e.g.. from the EU THOR (European Union Thermohaline Overturning – at Risk?) project (http://eu-thor.eu/) will provide some information about the requirements for ocean heat content in the context of decadal forecasting. Preliminary studies at the Met Office Hadley centre have shown that temperature observations below 2000 m improve decadal forecasts [66] of future OHC change [Dunstone, pers. comm.].

Table 1: GCOS Observation Requirements in WMO/CEOS Database for upper ocean temperature and salinity. Each requirement is expressed in terms of Horizontal Resolution, Vertical Resolution, Observing Cycle, Delay of Availability and Accuracy with each parameter described in terms of Goal (GL), Breakthrough (B/T) and Threshold (T/H). Available from http://www.wmo.int/pages/prog/gcos/.

	Horiz. Res.			Vert. Res.			Obs Cycle			Delay of Avail.			Accuracy		
	GL	B/T	T/H	GL	B/T	T/H	GL	B/T	T/H	GL	B/T	T/H	GL	B/T	T/H
Temperature	1 km	6 km	300 km	1 m	2 m	10 m	1 day	2 days	10 days	0.5 hrs	0.6 hrs	1 hrs	.001 K	.002 K	.01 K
Salinity	15 km	40 km	300 km	1 m	2 m	10 m	1 day	2 days	10 days	0.5 hrs	0.6 hrs	1 hrs	0.001	0.002	0.01

Nevertheless, the priority climate indicators and associated accuracy requirements need to be identified by the climate community.

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