Recent progress and the current status of global ocean observations of temperature, heat content, and steric sea level

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Ocean temperature and climate

Temperature is the most fundamental of ocean variables as an index of the present state of the Earth’s climate system and of its variability and change. About 341 W/m\(^2\) of incoming solar radiation is nearly balanced by the sum of reflected and outgoing longwave radiation, with an incoming excess less than 1 W m\(^{-2}\) (e.g. Trenberth and Fasullo, 2009). Over 90% of this energy increase is stored in the oceans (Levitus et al., 2012, Church et al., 2011) because of the high heat capacity of seawater and the capability of ocean circulation and mixing to transport heat away from the sea surface and sequester it in the deeper layers. Much smaller amounts of heat are stored in the atmosphere and the land or as latent heat for melting ice. For these reasons ocean heat content is a direct and quantitatively accurate index of change in the climate system. Large changes in regional and global ocean heat content are seen on seasonal, interannual, and decadal to multi-decadal timescales.

Another role of ocean temperature change is through its contribution to sea level. The multi-decadal increase in global sea level has a substantial component due to ocean warming. That is, increasing sea level is due partly to increasing mass of the oceans through melting of glaciers and ice sheets. The rest is caused by changes in the density of seawater dominated by thermal expansion. Because of their different causality, magnitudes, and timescales, for understanding sea level, ocean observations must quantify not only sea level change but also its component contributions and their regional patterns.

A third key role of temperature is as a dynamical variable in ocean circulation. The strength of ocean currents, relative to layers deeper in the water column, varies in proportion to the horizontal gradient of sea water density. The density gradients are dominated by temperature in most of the World Ocean. Hence, temperature is the primary variable for detecting and diagnosing changes in the strength and location of ocean currents. In the historical records of the oceans, direct measurements of ocean current are much scarcer than indirect (geostrophic) estimates based on measurements of temperature or of temperature and salinity. A separate white paper considers observations of ocean circulation.

Finally, sea surface temperature (SST) is of particular importance in determining air-sea exchanges of both heat and moisture. In effect, the surface ocean controls the temperature of the lower atmosphere, and helps to determine the strength of the global hydrological cycle through evaporation. Warm tropical SSTs drive convection in the overlying atmosphere, contributing to a range of phenomena from tropical cyclones to interannual El Nino/Southern Oscillation variability.

Changes in temperature are of interest not only as characterizing the physical state of the oceans, but also because of their impacts on marine ecosystems. These impacts may be direct, on geographic distributions of temperature-sensitive species, and also indirect if the temperature and density vertical structure of the upper ocean changes in ways that influence the supply of nutrients to the euphotic zone.
A community-wide review (Wijffels et al., 2010) of observations of ocean temperature and heat content was carried out through the OceanObs'09 process (Hall et al., 2010). Here we will not repeat the Wijffels et al. (2010) review, but will update that work, noting the substantial progress made in the past three years in (i) improved estimates of change based on historical temperature observations, (ii) expanded implementation of ocean temperature observations based on the community consensus, and (iii) work toward designing the final elements required for a comprehensive global ocean observing system. All of these threads of progress are considered in the following.

**Improved estimates of the past changes in heat content and steric sea level**

The historical record of ocean temperature profile data is very sparse in coverage, both spatially and temporally. Until recently, these data were limited by the need for a ship or a fixed mooring to be present in order to collect them. The sparse coverage was mitigated to some extent in the 1970’s – 2000’s by the use of eXpendable Bathy-Thermograph (XBT) probes deployed from many commercial ships. XBT sampling extended the density of coverage but at the cost of lower accuracy in temperature and depth estimates. A revolutionary advance the profiling float, enabling global observations to be made by the Argo Program using highly accurate conductivity-temperature-depth recorders (CTDs) deployed on autonomous instruments having multi-year lifetimes. Recent progress with the pre-Argo temperature record includes ocean warming estimated for an extended time span of 135 years, as well as improved characterization of uncertainties based on coverage and measurement biases. In particular, progress has been made toward closing global budgets of energy and sea level change on multi-decadal timescales.

**The past 135 years** – The first global-scale measurements of subsurface ocean temperature were made by HMS Challenger during 1872-1876, consisting of more than 300 temperature profiles made in all three oceans. Average along-track differences between modern Argo data and Challenger measurements (Roemmich et al., 2012) were 0.59°C ± 0.12 at the sea surface, consistent with other historical analyses of global SST, diminishing to 0.39°C ± 0.18 at 366 m and 0.12°C ± 0.07 at 914 m. The large magnitude of warming, greater in the Atlantic than in the Pacific, and double the estimates for the past 50 years, suggest that it began about 100 years ago rather than in recent decades.

**The past 50 years** – Continuous but irregular and sparse sampling of temperature on global scales, but with a distinctly northern hemisphere bias began about 50 years ago. A recent analysis by Levitus et al (2012) for the depth range 0-2000m, includes historical data not previously available, adds modern data, and applies improved corrections to XBT depth estimates. World Ocean heat content increased by 24.0 ± 1.9 x 10²² J during 1955-2010 (Figure 1), corresponding to a rate of 0.27 W/m² per unit area of earth’s surface. Thermal expansion over this period was found to contribute 0.54 ± .05 mm yr⁻¹ to global sea level.

Other recent analyses include those by Church et al (2011), and Ishii and Kimoto (2009). The former study (updating estimates of Domingues et al., 2008) estimated the full-depth steric sea level component to be 0.80 ± .15 mm yr⁻¹ (Figure 1) and full-depth warming of 19.3 x 10²² J during 1972-2008. The larger rates here, relative to Levitus et al. (2012), are mostly attributable to the different time interval for linear trend analysis, there having been relatively little warming and high uncertainty due to lack of data in the period 1955-1972. **The past 20 years** – The period from the early 1990’s to the present is a better-observed interval because it is bracketed by the World Ocean Circulation global hydrographic survey, 1991-1997, and the modern Argo Program. Moreover, the continuous record of satellite altimetry provides very accurate measurements of sea surface height for closing the sea level budget. Lyman et al. (2011) considered estimates of 0-700 m
global ocean heat content made independently by several groups. Differences between estimates were identified by cause, including XBT fall-rate errors and interpolation techniques. Net warming for the period 1993-2008 was found to be 0.64 ± 0.11 W m\(^{-2}\) (average over the earth’s surface area). It is not certain whether the apparent increase in warming since 1993 represents accelerated warming or whether the pre-1993 value was under-estimated due to sampling deficiencies. In addition to the upper ocean warming, Purkey and Johnson (2010) estimated deep ocean warming of 0.03 W m\(^{-2}\) (of earth surface area) below 4000 m in repeat hydrographic transects.

The present era - The recent record is distinguished by having not only Argo and altimetric height measurements, but also satellite measurements of gravity (GRACE) for estimation of the mass-related component of sea level. Good agreement between total sea level and its steric and mass-related components is shown by Leuliette and Miller (2009) as updated in Merrifield et al (2010, Figure 2), and by Cazenave et al (2009).

For the period 2006-2011 having high spatial coverage without seasonal biases, analyses of Argo data (as in Roemmich and Gilson, 2009) indicate an increase in 0-2000 dbar average temperature of 0.01 °C, and a trend in steric height (0/2000 dbar) of 0.5 mm yr\(^{-1}\). The temperature trend, 2006-2011 (Figure 2), was 0.01 °C yr\(^{-1}\) at the sea surface, decreasing to 0 at 400 dbar, then increasing again to >0.001 °C yr\(^{-1}\) from 800 to 1800 dbar. Over this short period of time, the trend is strongly influenced by interannual variability and may not be representative of a longer Argo record. However, the rates of warming and steric increase are consistent with the historical rates as described above.
Present-day observations of ocean temperature

The Argo Program’s array (Freeland et al., 2010), presently consisting of 3500 active profiling floats (Figure), is the core of the global ocean observing system for temperature, heat content, and thermosteric sea level. The Argo array is close to its initial design of 1 float per 3° x 3° in deep ocean areas from 60°S to 60°N, profiling from 2000 m to the sea surface every 10 days. In addition, there are Argo floats operating in some marginal seas, and coverage at lower resolution has been extended poleward of 60° into the seasonal ice zones. All Argo data is freely available in near real-time and delayed-mode versions. The temperature accuracy specification in Argo floats is 0.002 °C with stability of .0002 °C yr⁻¹. For pressure the accuracy specification for Druck sensors deployed since 2003 is 2 dbar. The accuracy of pressure, including larger drifts resulting from an oil “microleak” in about 30% of floats deployed from 2007-2009, is described and assessed by Barker et al. (2011).
Shipboard repeat hydrography is the gold standard for high accuracy and top-to-bottom sampling of temperature, salinity, and pressure, as well as other parameters. A sparse network of repeat transects is re-occupied on decadal timescale (Hood et al., 2010), and coordinated by the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP, [http://www.go-ship.org](http://www.go-ship.org)). This program, together with other non-repeating shipboard hydrography, provides the only dataset at present for observing temperature changes below 2000 m (e.g. Purkey and Johnson, 2010), and is also a critical dataset needed for delayed-mode quality control in Argo floats.

Ice-tethered profilers are an analogous technology to Argo floats for regions with year-around ice cover, where profiling floats cannot operate. About 20 ice-tethered profilers are presently operating in the Arctic Ocean ([http://www.whoi.edu/website/itp/overview](http://www.whoi.edu/website/itp/overview)). Another technique for high latitude temperature profiling is the use of animal-borne sensors (Boehme et al, 2010), and these have provided
temperature data in seasonal ice regions where alternative techniques are problematic.

Other observational networks also provide complementary observations to the Argo/GO-SHIP core datasets in order to meet specific requirements. The Global Drifter Network, presently including 988 buoys, provides measurements of SST that are needed for calibration of satellite SST observations, with spacing at about 5° x 5°. Tropical mooring arrays in the Pacific, Atlantic and Indian Ocean, provide temperature observations with high temporal resolution from 0 to 500 m, in conjunction with marine meteorology at the same buoy locations. These moored arrays address both research and operational objectives, largely for seasonal-to-decadal variability in air-sea exchanges and wind-forcing in the tropical oceans. The historical broadscale XBT networks have largely been replaced by Argo, but modern High Resolution and Frequently Repeating XBT Networks (Goni et al., 2010) are primary sources of repeating temperature data on short spatial scales including in the western boundary currents, eastern boundary currents, and the Antarctic Circumpolar Current.

**Future evolution of the observing system for temperature**

The goal for the future ocean observing system with respect to temperature, heat content, and steric sea level variations is to extend the present system to truly global coverage. The requirement is for substantial extensions in depth to 6000 m, in latitude to include seasonal and fast ice regions, and for inclusion of all marginal seas and ocean margins.

**Deep Ocean:** Development work is underway of Deep Argo floats capable of at least 150 cycles to 6000 m, and of CTDs capable of maintaining very accurate calibration for deep ocean applications. Following deployment of engineering prototypes, one or two deep basins (> 5000 m) will be selected for pilot study, on the basis of identified deep ocean temperature trends (Purkey and Johnson, 2010), favorable signal-to-noise in deep temperature, and accessibility. Pilot deployments will be made to determine the required sampling requirements for global deployment, as well as to verify the capabilities of the new floats and sensors. Deep Argo should be a global array capable of observing decadal variability and multi-decadal change, while being complementary to shipboard repeat hydrographic sampling.

**High latitude oceans:** Recommendations for observing systems in both the Arctic and the Southern Ocean have been made at OceanObs'09 (Lee et al., 2010, Rintoul et al., 2010), and are being updated by those implementation groups. For the Southern Ocean, a strong recommendation was to extend Argo sampling at nominal density southward, including seasonal ice regions through the use of ice-avoiding and ice-capable floats and acoustic tracking. Float deployment opportunities are very challenging south of 4°S, and require special attention. In some regions, the use of animal-borne sensors and/or ice-tethered profilers may also be effective and regionally appropriate. Similarly, in the Arctic, the same combination of autonomous profiling technologies is needed to extend temperature profiling at Argo-like resolution across all of this critical region.

**Marginal seas:** Recent technology advances in profiling floats, including greatly shortened surface times in floats with Iridium communications, decreases the likelihood of grounding or beaching. Grounding was a limiting factor in early float deployments, and it is now practical and valuable to deploy Argo in the marginal seas. Some unsampled marginal seas such as those of the Indonesian archipelago, are large enough, and have strong enough interannual variability to impact global heat and freshwater budgets. International agreements and partnerships are critical for access to the marginal seas. Arrays with resolution greater than Argo's may be appropriate for some marginal seas. Very high resolution profiling can be obtained using glider technology, but this is generally most appropriate for studies of velocity
and circulation (see white paper on that topic) rather than temperature and heat content.

**Boundary current regions:** Cronin et al. (2010) considered requirements for sampling in western boundary current (WBC) extension regions for air-sea interactions. Due to the high eddy variability in these regions, higher spatial/temporal resolution is needed here than in the ocean interiors. Sampling with profiling floats in the Kuroshio Extension System Study (KESS), together with Argo floats in that region, has provided a practical example of enhanced resolution sampling (roughly twice Argo resolution). Comparable arrays are needed in all WBC regions, and these are now becoming feasible due to enhanced lifetime in new-generation Argo floats. Battery lifetimes of 400 cycles can provide more than 5 years of sampling at 5-day cycling. As noted above for marginal seas, high resolution profiling by gliders is planned for boundary current sampling, as applicable to studies of velocity and circulation.

**References**


Roemmich, D., W.J. Gould and J. Gilson (2012), 135 years of global ocean warming from the Challenger Expedition to the Argo Program Nature Climate Change, DOI: 10.1038/NCLIMATE1461.
