2.1: *In-situ* Ocean Observations: A brief history, present status and future directions

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Abstract

Observations at and below the surface of the oceans are essential for understanding the ocean system and the role played by the ocean in earth's climate, for documenting changes and for initialising, validating and improving ocean models. It is only since the late 20th century that, thanks to advances in microelectronics, battery technology and satellite communication *in-situ* observations, (together with satellite observations), have reached a volume and spatial distribution that allows us to track a wide range of global and regional phenomena. This review traces the development of *in-situ* ocean observations primarily from a physical standpoint and describes the internationally co-ordinated observing networks that now supply these observations. It considers the enormous changes that have occurred in the volume and distribution of these observations and the implication of these changes for defining the evolving state of the global ocean. Finally there is discussion of the prospects for further improving sustained ocean observations and for the delivery of integrated information from interrelated observing networks.

1. Introduction

Observations of the interior of the ocean are fundamental to understanding ocean dynamics and properties, to monitoring changes in the oceans' state, (whether caused by natural or human influences), to quantifying the forcing at the atmosphere-ocean (in some areas, atmosphere-ice-ocean) boundary and for determining the role and importance of the ocean in the climate system. *In-situ* ocean observations also complement and provide ground truth for remotely-sensed observations of the ocean from earth-observing satellites (Chapter 2.2). Both satellite and *in-situ* observations are vital for ocean forecasting, ocean reanalysis and for assessing the fidelity of ocean and earth-system models and underpinning their future improvement (Chapters 5.2 and 5.3).

The technical and logistical challenges of making *in situ* ocean observations are legion; measurements often have to be made in areas far removed from land, in a corrosive liquid, at great pressure and in a fluid that is effectively opaque to electromagnetic radiation. Capturing the oceans' variability requires repeated measurements over wide areas and yet with small spatial resolution. Detecting change demands measurements of high precision and stability over decadal and longer time scales. For these reasons the history of scientifically-focussed, open ocean observations is relatively short: it may be said to have started with the voyage of *HMS Challenger* in the 1870s. (Wyville Thompson and Murray, 1885)

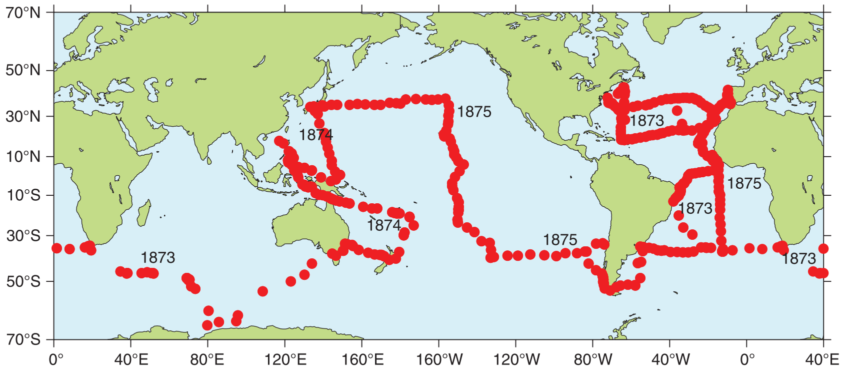

Figure 1. Track of *HMS Challenger*. This was the first major scientific exploration of the global ocean. The voyage lasted 4 years and covered more than 68,000 nautical miles.

Through the 20th century, measurements became more accurate but remained relatively sparse and regionally focussed until the 1990s. During that century there were a number of initiatives and technical advances that, with hindsight, can be regarded as having been crucial steps in improving our ability to make systematic measurements within the global ocean. Often the driver for progress was the sequence of *"New observations lead to new understanding – new understanding points out the inadequacy of earlier observations – this understanding stimulates new technical development"*. The other major driver for progress was the application of advanced technologies to the oceans – solid state electronics in the 1960s and 70s, miniaturised computing power, and satellite communication and navigation from the 1990s to the present day. Innovative exploitation of these advances has led to major advances in our observational capability. In the following we briefly review the development of key observing technologies (section 2) and their impact on the number and distribution of ocean observations (section 3). Apart from the ever-present uncertainties of funding, the future for sustained ocean observations through the exploitation of emerging technologies (Section 3) and within the new Framework for Ocean Observations (section 5) is bright.

2. Development of present observational capability

Rather than considering the advances in observational capability on a parameter-by-parameter basis we will discuss the topic through a brief chronology of some of the most important technical developments that have enabled the establishment of the present multi-parameter ocean observing systems. In recent years progress has often been made in a number of key ocean parameters simultaneously through the mounting of major internationally coordinated observational programmes and/or the adoption of new generic observing platforms or technologies.

2.1 Late 19th to mid 20th centuries

Improvements in navigation were the first drivers of systematic ocean observations. In the 19th century, following the introduction of Harrison's chronometer that enabled longitude to be determined, it became possible to estimate surface currents from a vessel's navigation and these were recorded in navigational logs. Such observations led to the compilation of surface currents in the Atlantic by James Rennell and published (1832) posthumously by his daughter and more widely by Mathew Fontaine Maury (1855). The major motivation for Maury's work was not scientific but was to use knowledge of surface currents to shorten sea voyages and hence gain commercial advantage. This was also a driver for the measurement of ocean temperatures since it was recognised by Benjamin Franklin that temperatures changed across the Gulf Stream and that by navigating into water of the correct temperature ships could speed their voyages between America and Europe. Early ocean surface temperature measurements were made by dipping a simple mercury-in-glass thermometer into, first, wooden and later canvas buckets of water collected from the sea surface: a technique that remained in common use until the mid-late 20th century. While wooden buckets were well insulated, canvas ones were less so and thus these temperature measurements are now known to be biased low due to evaporative cooling.

The ability to make subsurface observations of temperature and salinity developed substantially between the pioneering voyage of *HMS Challenger* (1872-6), the Meteor expedition to the Atlantic (1925-27) (Wüst, 1935), and *Discovery* investigations in the Southern Ocean (starting in 1925) (Herdman, 1948). Most temperature measurements on *Challenger* were made with Six's maximum/minimum thermometers under the erroneous assumption of a monotonic decrease of temperature with depth. A small number of Negretti and Zambra reversing thermometers were also used on the Expedition (see Rice 2001) and these subsequently became the standard method for determining subsurface temperatures until the 1970s. Carefully calibrated reversing thermometers could determine temperature to at best about 5 millidegrees. The difference between paired thermometers (one protected against pressure effects and the other unprotected) allowed the depth of the measurement to be determined to within 10m.

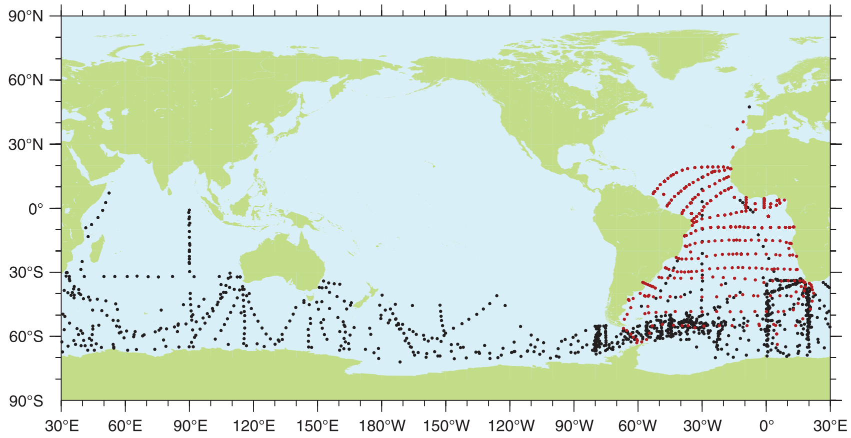

Figure 2. Stations worked during the Meteor Atlantic Expedition (red) and by the Discovery Investigations (black) (From NOAA WOD)

On *HMS Challenger*, salinity was determined by measuring density using a hydrometer and converting this value to a quantity of total dissolved solids. In 1902 the International Council for the Exploration of the Sea (ICES) was established to investigate the relationship between physical ocean properties and fisheries in the Northern Atlantic. One of ICES' earliest and most significant contributions to physical oceanography was the work of Martin Knudsen in standardising the determination of salinity by titration against silver nitrate solution and building on the investigation of seawater chemistry by Dittmar (1884) and Forchhammer (1856). A Standard Seawater Service was established by ICES, the successor organisations of which continue to provide the internationally accepted standard to the present. (http://www.sea-technology.com/features/2011/0611/salinity.php)

Subsurface water samples were collected and thermometers deployed using strings of typically up to 12 water sampling bottles clamped to a wire and sequentially triggered to close the bottles and reverse the thermometers by weights (messengers) sliding down the wire. In deep water multiple casts could be deployed at each station to sample the full ocean depth but even so the deepest measurements were commonly separated by several hundred metres. Many designs of sampling bottle were used but by the 1920s, the Nansen bottle had become the generally-used standard. Water samples were drawn from each bottle (occasionally with duplicates) and stored for analysis by titration (for salinity) either at sea or the end of the voyage. The Nansen bottle/reversing thermometer combination was used virtually unchanged until the 1960s/70s when continuous profiling was introduced together with multisampler cassettes and plastic sample collection bottles. (See Section 2.2)

Wüst (1935), using data from the Meteor Expedition that included dissolved oxygen (Winkler, 1888), developed the "core method" by which the spreading of subsurface water masses was inferred by tracing ocean property distributions. Velocity could not be determined in absolute terms below the ocean surface but vertical shear could be estimated by the dynamical method – geostrophy (Sandström and Helland-Hansen, 1903).

The next technological development that added substantially to the inventory of ocean observations was the mechanical bathythermograph invented by Athelstan Spilhaus in 1937 (Spilhaus, 1938) and developed further by Al Vine of the Woods Hole Oceanographic Institution during the early 1940s. This instrument enabled the thermal stratification of the upper 150 m of the ocean to be determined, firstly from submarines and later from underway surface ships, and made possible predictions of underwater sound propagation. The technology was simple, a bourdon tube for pressure, a bi-metallic strip for temperature and the results scribed on a smoked glass slide. This instrument was eventually used systematically by the scientific community to make a major contribution to understanding the spatial variability, for example, of the Gulf Stream (Fuglister, 1963).

2.2 Second half of 20th century

The advent of solid state electronics and the use of "O"- rings to seal pressure cases had a profound effect on oceanographic instrumentation. It enabled small, battery-powered electronics to be fitted into modestly sized instruments. One of the first applications in the field of ocean physics was the development of Swallow's neutrally buoyant floats with which he made the first, absolute measurements of deep currents.[1] (Swallow 1955) and then to discover (Crease 1962) the first evidence of the existence of an energetic ocean dominated by mesoscale variability.

Technical development accelerated in the 1960s and early 1970s, leading to observational methods that we now regard as routine and greatly enhanced by improvements in navigation: LORAN and Decca Navigator in the 1960s followed by Transit satellite navigation in the 1970s. This meant for the first

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[1] Prior to 1955 measurements had been made by primitive recording current meters lowered from anchored ships. Such records were short and contaminated by navigational uncertainties. They could be summarized in a single one-page table (Bowden, 1954).

time that we knew (to an accuracy better than 1km) where observations had been made and thus it was possible to make greatly-improved estimates of surface currents. Chemical titrations for the determination of salinity were replaced by salinometers measuring electrical conductivity (Park and Burt, 1965) and the traditional water bottle/reversing thermometer combination started to be replaced by continuous temperature and salinity profilers - the Conductivity (Salinity), Temperature Depth (C(S)TD) instrument. The first were inductive STDs, such as that marketed commercially by Bissett Berman, and these were followed in the early 1970s by the Neil Brown CTD that used a conductivity sensor with greater stability. Calibrations of measurements from these profilers still depended on mercury-in-glass thermometers and, in the absence of multiple samples in the vertical, were often limited to only a deep and shallow calibration point in each profile.

The limited measurements of deep ocean currents by Swallow's ship-tracked floats (lasting a few days and covering distances measured in tens of kilometres) were later enhanced by floats tracked over many months from fixed listening stations using low frequency sound propagation through the SOFAR channel. The CTD and SOFAR floats were developed specifically for use during the Mid-Ocean Dynamics Experiment conducted near Bermuda and allowed the first mapping of the ocean mesoscale velocity field (The MODE Group, 1978). Later the SOFAR float measurements were simplified by using fixed sound sources and receivers on drifting RAFOS (SOFAR spelled backwards) floats, (Rossby, Dorson and Fontaine, 1986).

By the late 1960s the mechanical bathythermograph started to be replaced by the eXpendable bathythermograph (XBT). The XBT measured temperature with a thermistor and estimated depth as a function of time using a fall-rate algorithm. The probe relayed its data to the deploying ship through a thin 2-conductor copper wire spooled from reels on both the probe and the ship. The initial XBTs (model T4) reached approximately 450 m while later models reached greater depths. The majority of such probes were used by navies in anti-submarine operations but large-scale civilian use rapidly developed in experiments such as TRANSPAC**.** Such measurements greatly increased our knowledge of upper ocean variability (e.g. Koblinsky et al., 1984, Talley and White, 1987). However the reliance on fall rate algorithms was later revealed to be problematic when attempts were made to merge these data with other sources in which pressure (depth) was measured directly (Wijffels et al., 2008).

Surface temperature measurements by ships were, by this time, being made using sensors inserted into the engine cooling water intake and recorded automatically. While generating more data, these measurements also introduced uncertainty due to the widely differing depths of these intakes on large and small ships together with thermal contamination from the ships' machinery. This latter factor was later reduced by the use of hull contact sensors (Kent et al., 1991). The process of defining what is meant by "sea surface temperature" is complex and was brought into sharp focus by the challenges of providing ground truth for satellite observations in which the measurement is of the skin temperature rather than a bulk interior value (Donlon et al., 2002). Following the advent of satellite SST measurements these and *in-situ* data were combined to produce global climatologies of which that by Reynolds (1988) was an early example. Today the GODAE High Resolution Sea Surface Temperature consortium (GHRSST - www.ghrsst.org) seeks to produce and improve such climatologies.

The period of the 1960s and 1970s also saw significant advances in the measurement of subsurface ocean currents using moored instruments. Micro-electronics allowed the development of internally recording (on magnetic tape) current meters. Two current meter designs dominated the field in the west; the Aanderaa RCM4 and the Geodyne, while in the Soviet Union, the mechanical Alekseev instrument was used extensively. However, up until the 1980s individual records, rarely exceeded 30 days and significant differences in instrument response dependent on mooring type – with surface or subsurface buoyancy – were found. This led to the development of vector-averaging current meters that significantly reduced the wave-induced contamination of records from surface moorings. Together these technologies allowed major experiments (Polygon (1970), Mid-Ocean Dynamics Experiment

(MODE) and POLYMODE (1973-78)) to explore and map the oceans' mesoscale variability (The MODE Group, 1978), Kamenkovich, (1986), Freeland and Gould, (1976)).

During the 1970s first the NIMBUS and later the more accurate TIROS series of satellites started to provide global instrument tracking by measuring the Doppler shift of radio signals. The method was used to reveal the paths of surface drifters and ultimately developed into the Argos tracking system. Regional experiments used this technology: NORPAX in the North Pacific starting in 1975 (McNally et al., 1983), followed by a Gulf Stream Experiment in 1978 (Richardson, 1983) and culminated in the internationally co-ordinated deployment of 300 drifters in the Southern Ocean in 1978-9 as a contribution to the First GARP (Global Atmospheric Research Project) Global Experiment (FGGE), (Garrett, 1980). While the FGGE buoys collected surface temperature and atmospheric pressure data, the quality of the near-surface velocity data suffered from the large size of the float bodies (windage), the poor performance of the "window-shade" drogues and the inability to detect without ambiguity if the drogue was still attached. (The technological developments during this era are described by Baker, 1981).

Throughout the 1980s various combinations of moored current meters and neutrally buoyant floats, CTD profilers, expendable probes and surface drifters were used in a wide range of regional experiments. For example the Tropical Ocean Global Atmosphere (TOGA) project was a concerted effort to collect data from the equatorial Pacific combined with numerical modelling, aimed at understanding and predicting the evolution of the El Niño - Southern Ocean (ENSO) phenomenon. TOGA significantly enhanced the collection and distribution of *in-situ* sea level data, temperature profile data from XBT probes but most importantly led to the deployment of the Tropical Ocean Atmosphere (TAO, later TAO-TRITON) array of moorings measuring and reporting real-time upper ocean and atmospheric data (McPhaden et al 1998). The array has now expanded to cover the Atlantic and Indian Oceans (http://www.pmel.noaa.gov/tao/global/global.html). See section 2.3

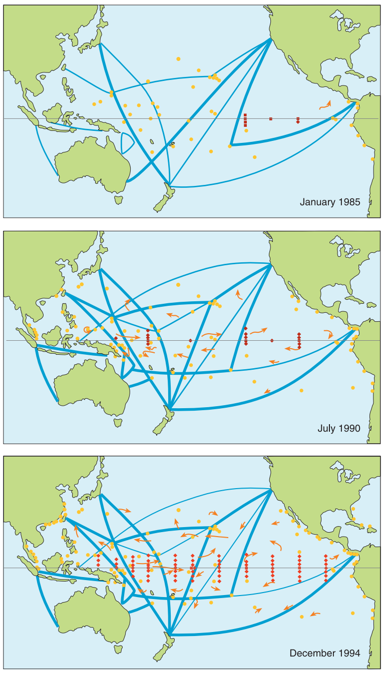

Figure 3. The evolution of the TAO-TRITON tropical Pacific Ocean observing system. (Top) The observing system at the beginning of the TOGA program in 1985, (middle) the evolving observing system in 1990 and (bottom) the sustained observing system that now comprises the TAO-TRITON observing system.
Key. XBTs from volunteer observing ships; (blue lines) , Coastal tide gauges (yellow dots); Drifting buoy (curved arrows) ; Current meter, temperature and salinity moorings and surface flux stations (red diamonds). (From McPhaden et al., 1998).

The insights into ocean variability gained during the 1960s, 1970s and 1980s highlighted the problems of interpreting sparsely sampled *in-situ* data and of detecting long-term change in the oceans (Wunsch, 2001). It was the prospect of satellites carrying radar altimeters (as had been heralded by the brief 1978 SeaSat mission (See Chapter 2.2)) that led for the first time to the planning of an almost global scale programme - the World Ocean Circulation Experiment (WOCE) – that aimed to improve models of the oceans' role in climate by collecting comprehensive remote sensed and *in-situ* data (Thompson et al., 2001).

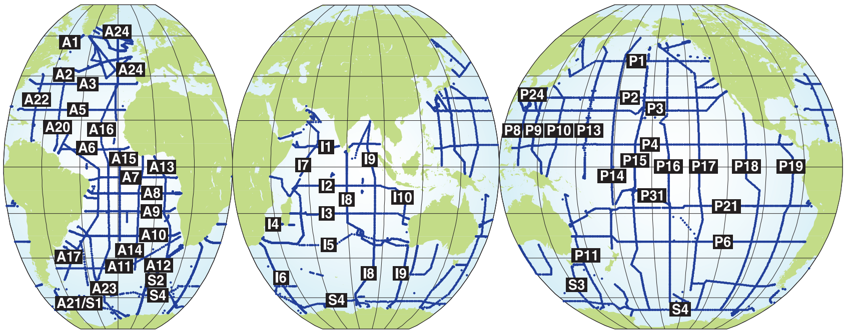

Figure 4. The WOCE One-Time hydrographic sections. Each line consisted of full-depth stations at typically 100km spacing measuring temperature, salinity, nutrients and a suite of chemical tracers.

Improved understanding of the oceans' role in climate-related variability from WOCE-derived data has been well-documented in the various chapters of Siedler, Church and Gould (2001) but it is worth noting that the strength of WOCE, in terms of producing a global scale data set, is that the resulting data serves as a baseline against which past and future change may be assessed. Given this, considerable effort was made during WOCE to ensure high quality and internal consistency of the project's data sets. WOCE incorporated a number of sub-programs including ship based hydrographic sections, western boundary current mooring arrays and XBT and surface drifter programs (the latter jointly with TOGA). In particular the quality and comprehensiveness of temperature, salinity and ocean chemistry data in the WOCE Hydrographic Programme (WHP) (Figure 4) in conjunction with the Joint Global Ocean Flux Study (JGOFS) (King, Firing and Joyce, 2001) was unprecedented. These data were subsequently described in a series of four atlases (Sparrow, Chapman and Gould, 2012).

The most innovative and significant technical advance during WOCE was the development of a neutrally buoyant float that did not depend on acoustic tracking and hence could be deployed on a global scale. The Autonomous, LAgrangian Circulation Explorer (ALACE) floats, (Davis, Webb, Regier and Dufour, 1992), were ballasted to drift at depths around 1000 m and programmed to surface at regular intervals by changing their buoyancy. Once at the surface, their positions were fixed by satellite (Argos tracking). Successive surfacing positions gave a measure of the time-averaged ocean currents for each drift segment. These floats allowed for the first time the collection of subsurface velocity data across entire ocean basins (Davis, 1998). Later in WOCE, the floats started the collection of, first, temperature and later temperature and salinity profiles acquired as the floats rose to the surface. In 1998 the Profiling ALACE (PALACE) float was envisaged as the means of building a global array that would provide unprecedented observations of the upper 2000m of the open oceans (Argo Science Team, 1998).

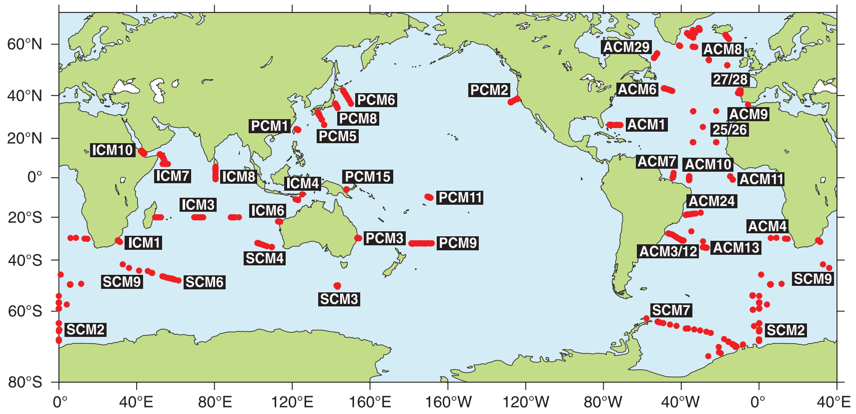

Figure 5. WOCE moored current meter arrays. Most mooring arrays were deployed for approximately two years. In many locations these arrays provided the first timeseries of ocean velocity, temperature and salinity.

In the 1990s the WOCE and TOGA programmes also provided an impetus for the systematic global-scale use of moorings. Since the 1980s technology had matured to allow for deployments of full-ocean-depth moorings carrying a range of self-recording instruments to observe variability of currents, temperature, salinity and pressure. In WOCE, arrays of moorings across several "choke points" (geographic constrictions of important ocean flows) documented the transports of deep and shallow boundary currents and flow through passages and gaps as well as contributing to trans-basin transport estimates. Retired ocean telephone cables complemented the choke point observations so as to observe changes in conductivity-weighted ocean transports. For example, more than 30 years of Florida Strait transport using this technique have made a significant contribution to documenting parts of the upper limb of the Atlantic subtropical gyre transport (Meinen et al., 2010). In the tropical Pacific, the TOGA moored array reached full implementation to record the state of the equatorial thermocline and provide real time information of winds to support seasonal El Niño forecasting.

The late 1980s and early 1990s also saw the development of moored and ship-mounted Acoustic Doppler Current Profilers (ADCP) for the observation of ocean velocity profiles. The ADCP measures ocean currents using sound waves to detect the Doppler effect from small scattering particles in the ocean; as particles move toward or away from the sound source, the frequency of the return signal is either higher or lower. Assuming that the particles are advected by the ocean currents, the frequency shift is proportional to the speed of the current along the axis of the acoustic beam. Combining information from 3 or more beams allows derivation of the ocean velocity in all three coordinates. As the emitted sound travels through the water column, the ADCP measures the current at many different depths simultaneously.

The full exploitation of ship-mounted ADCPs was dependent on the arrival of another enabling technology; the Global Positioning System (GPS). This became increasingly available to civilian users during the 1990s and as well as enabling absolute positions to be determined instantaneously to metre accuracy, ship's heading could also be determined with an accuracy far better than from previously-used gyro-compasses. This provided the information needed to accurately determine the speed and direction of the ship over the ground and enabled ADCPs to be mounted on research vessels to provide underway upper-ocean velocity (to 800 m) observations. From the 1990s onwards ADCPs were also incorporated in CTD/multisampler packages allowing velocity to be determined throughout the water column. (Fischer and Visbeck, (1993), King, Firing and Joyce, (2001)).

During the 1990s collaboration between WOCE and TOGA also led to an expansion of the collection of XBT data and significant improvements in the quality and quantity of data collected by surface drifters (See Chapter 4.2). As mentioned, the FGGE drifter extensively used in the 1970s did not provide high quality surface ocean velocity data. A standardised WOCE/TOGA drifting buoy to suit observational requirements for meteorological and oceanographic applications was designed and deployed and is largely responsible for the improved data quality of Lagrangian surface measurements (Sybrandy and Niiler, 1991 and Chapter 4.2**).**

Many of the physical observations established by WOCE and TOGA were eventually subsumed into the framework of the much broader CLIVAR (Climate Variability and Predictability) project, established in 1995 as a component of the World Climate Research Program (WCRP). CLIVAR's focus on the coupled ocean-atmosphere system and its interest in a broad range of time scales (from seasonal to centennial) inevitably diluted the momentum in full ocean depth observations gained during WOCE. However, a much broader agenda of sustained ocean observations was developed under the auspices of GOOS (Global Ocean Observing System) responding to the need to understand the ocean's role in climate as identified by WCRP, the Global Climate Observing System (GCOS) established in 1992 and by the United Nations Framework Convention on Climate Change, UNFCC. Observations were also increasingly required to be delivered in near-real-time for use in operational ocean information products to guide and safeguard marine operations and deliver short term ocean and weather forecasts. As the 20th century closed, there was a growing recognition of the potential to build on the observational capabilities that had been established for limited-lifetime scientific experiments so as to provide a framework for an emerging sustained ocean observing system.

2.3 21st century: consolidation of capabilities and growth of sustained observations

The ocean observations collected during WOCE and TOGA were used to document the importance of the ocean in regional and global climate on short (days) to longer (decades and centuries) time scales (e.g. Siedler, Church and Gould, 2001). Moreover, WOCE established the strong international collaborations amongst national research institutes and funding agencies that would be required if a coordinated ocean observing programme were to be established together with the systems needed to collate, quality control and distribute data. Building on the success of WOCE, the aspirations of CLIVAR, and the requirements from GCOS and UNFCCC, and the continuing technological developments, in 1999 the ocean community held the first international conference solely focussed on sustained ocean observations, the OceanObs'99 conference (Koblinsky and Smith, 2001). The Conference's goal was to provide the framework and to set feasible objectives for the establishment of the first decade of a sustained ocean observing system. The network of sustained ocean observations that emerged from this conference was organised primarily around observing platforms that had been developed during WOCE, TOGA and CLIVAR.

The major observational programs that were delineated at OceanObs'99 were:

- a program called Argo that sought to establish and maintain a global-scale array of floats similar to the profiling ALACE float developed in WOCE. The array of 3000 instruments (roughly one every 300x300 km in the ice-free oceans deeper than 2000 m) would collect profile data (temperature and salinity) to 2000 m at nominal 10 day intervals. The data would be freely available in real-time and in a climate-quality-controlled data set with a 6 month lag. Argo would also produce subsurface velocity estimates (The Argo Science Team, 2001).

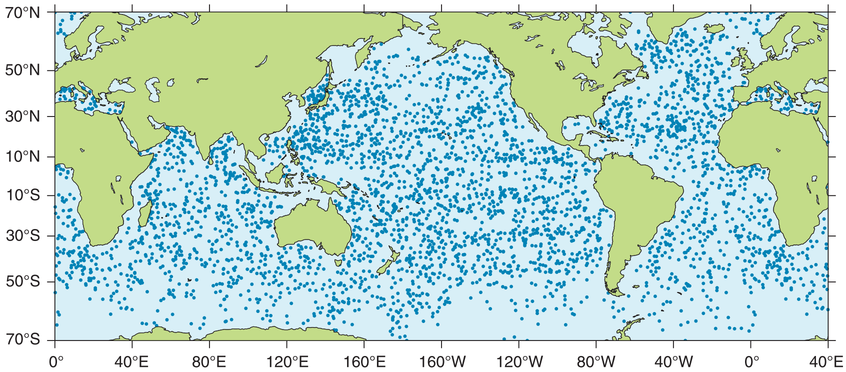

Figure 6. The array of Argo profiling floats that measure the temperature and salinity of the upper 2000 m of the ocean. Positions of floats that had delivered data within the last 30 days of March 2013. (Data from www-argo.ucsd.edu).

Argo reached its goal of 3000 operating floats by November 2007 and has since remained above that level (due in large part to the steady improvement in float operational lifetimes), thus providing continuous monitoring of the temperature, salinity, and velocity of the upper temperate and tropical oceans. The initial Argo design criterion of an array density of one active float per 300x300 km grid excluding regional seas and sea-ice zones has not yet been fully achieved since some areas remain over populated while other regions are under sampled. The success of Argo lies, not just in almost reaching design specification but in its data flow and quality control systems. Argo has successfully established a real time data stream regardless of the national provider of the particular floats and a delayed-mode stream of climate-quality calibrated data.

- A global XBT network that would focus on high resolution transects collecting temperature profiles in the upper 800 to 1000 m across ocean basins mostly using commercial vessels engaged in the Ship of Opportunity Program using semi-automatic XBT launchers. Although some XBT transects have been maintained for 30 years, the program was redesigned after the advent of Argo from a broad-scale sampling to a network with increased spatial and temporal resolution focusing on boundary and choke points currents or regions of high seasonal variability (tropical oceans) that would be complementary to the Argo global broad-scale array (Smith et al, 2001). Currently two modes of XBT transects are in operation: Frequently Repeated (RF), transects that are occupied 12-18 times per year with XBT deployment every 100-150 km, and High Density (HD) transects occupied 4 times per year with XBT deployment every 25 km.

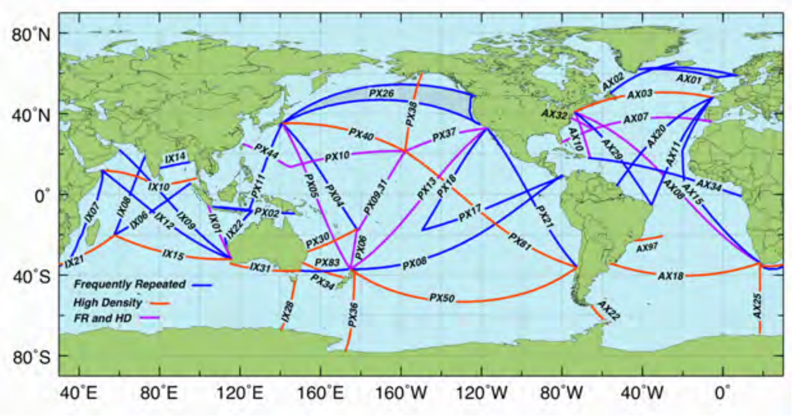

Figure 7. The present-day XBT network of transects across ocean basins. The XBTs are deployed from research vessels and ships of the Ship of Opportunity Program. The transects are sampled in two modes: High Density (HD) and Frequently repeated (FR). Some transects include time series with more than 30 years of data. (http://www.aoml.noaa.gov/phod/goos/xbt_network/index.php).

- Following on from WOCE and TOGA, a Global Surface Drifter Program was established that in 2005, reached the design density provided by 1250 drifters. The drifters are needed to anchor satellite-based measurements of sea surface temperature as a critical component of the GODAE High Resolution Sea Surface Temperature (GHRSST - www.ghrsst.org). In addition they are able to measure surface velocity. A subset of the drifters additionally observe atmospheric pressure and surface wind speed and direction. A dedicated data centre assembles and provides uniform quality controlled SST and surface velocity measurements. (This program and its contribution to surface current measurement are described in Chapter 4.2.)

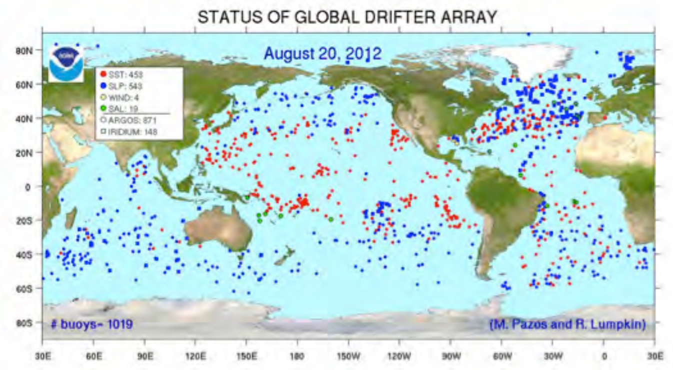

Figure 8. The global drifter array, as of August 20, 2012, that provides information of sea surface velocity, temperature and/or pressure. (Image from http://www.aoml.noaa.gov/phod/dac/index.php)

- There are a small number of locations where regularly repeated observations over long time periods have given insights into physical and biogeochemical ocean variability and also into the processes that connect the upper ocean to its deep interior. Notable among these are Hydrostation S (since 1954) and the Bermuda Atlantic Timseries (BATS) (since 1988) near Bermuda and the Hawaii Ocean Timeseries (HOT) (since 1988). More recent addition include the Cape Verde Ocean Observatory (CVOO) and the European Station for Timeseries in the Ocean (ESTOC) since 1994 near the Canary Islands. In addition some long-term observations were conducted from ocean weather ships that were instrumental to support early intercontinental air travel. The last weather ship, “Mike” in the central Norwegian Sea, was decommissioned in January 2010. Several of those sites have been continued with moored observatories, most notably ocean weather station “Bravo” in the central Labrador Sea and “Papa” in the Northeast Pacific

Building on these stations, and on the tropical surface mooring technology established during TOGA and the WOCE boundary current mooring arrays, OceanSITES (www.oceansites.org) was initiated at OceanObs’99 as a network of full-depth and surface time series at key climate-relevant locations (Send, et al, 2001). It has since developed into a global network of moorings at strategic locations in the ocean that measure a diverse range of ocean variables. This program now incorporates the

- Tropical moored arrays (Pacific - TAO/Triton, Atlantic - PIRATA, Indian -RAMA)

- Arrays monitoring the North Atlantic overturning (MOVE, RAPID-WATCH, 16°N, 53°N, Denmark Strait, Faroe-Shetland Channel and Fram Strait)

- Sites documenting water mass property changes such as those mentioned in the previous paragraph and similar long-term mooring/timeseries sites in the South Atlantic, Pacific, Indian, Arctic and Southern Oceans.

The time series from the observatories provide the means to develop accurate fields of watermass formation and transformation, as well as estimation of air-sea fluxes, and to allow quantification of the transports of major ocean current systems, and assessments of the variability of the vertical structure of the ocean and the role of eddy processes in the transport of heat and other properties.

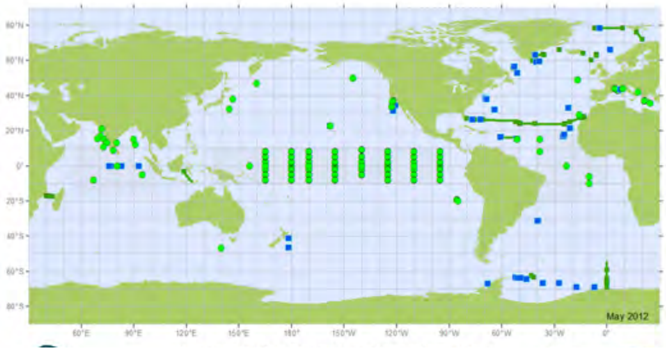

Figure 9. Map of operating OceanSITES time-series stations as of May 2012. OceanSITES is a worldwide system of long-term, deepwater reference stations measuring many variables and monitoring throughout the water column from air-sea interactions down to 5000 meters. (Image from http://www.oceansites.org/). (To be improved with high resolution version)

- At OceanObs'99, Gould, Toole et al. (2001) articulated the need for continued systematic ship-based survey of the global ocean. This plan was supported by CLIVAR, GOOS and the International Ocean Carbon Coordination Project (IOCCP) and has since resulted in a program of hydrographic sections based on the WOCE lines and re-occupied at 5-10 year intervals. The Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) (Hood et al., 2010) was formally established in 2007 to oversee the continuation of sustained ship-based hydrography and particularly addressed the needs of the community of scientists concerned with the ocean carbon and related chemical measurements. A global survey was completed in 2013 and reoccupation of sections are continuing. GO-SHIP (www.go-ship.org) is developing formal international agreements for a sustained international repeat ship-based hydrography program, including an internationally-agreed strategy and implementation plan; advocacy for national contributions to this strategy and participation in the global program and; providing a central forum for communication and coordination. GO-SHIP has brought up to date the manual of best practice for ship based hydrography first produced by WOCE. The establishment of GO-SHIP recognises that, despite numerous technological advances over the last several decades, ship-based hydrography remains the only method for obtaining the highest-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. Ship-based hydrography (and the sparse array of deep moorings) provide essential contributions towards documenting ocean changes throughout the water column. This is particularly important for the deep ocean below 2 km (52% of global ocean volume) that cannot yet be sampled by profiling floats although such floats are under development.

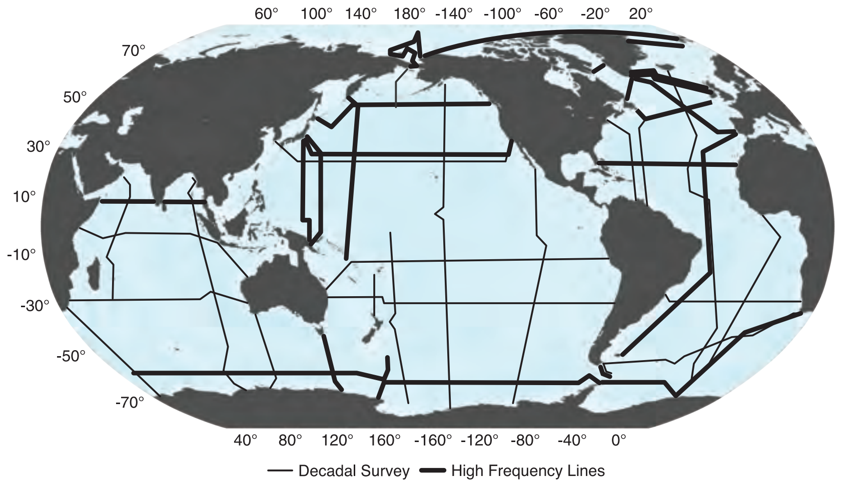

Figure 10. Repeat hydrographic sections of the GO-SHIP program. These sections are maintained by the cooperation of a number of countries with the objective of completing a global survey every 10 years. (Image from www.go-ship.org).

While these observing programs build on advances during the TOGA/WOCE era, two others have older roots.

- The systematic measurement of sea level extends back to the early 19th century and though such measurements were originally made in support of safe navigation, they now provide a valuable monitor of the consequences of changing ocean heat storage and an essential element of the ENSO monitoring and forecasting system. These measurements have, since the early 1990s been supplanted by systematic satellite altimetry but they remain an essential independent benchmark. (These topics are discussed in detail elsewhere in this book (Chapters 2.2, 4.5 and 6.1).)

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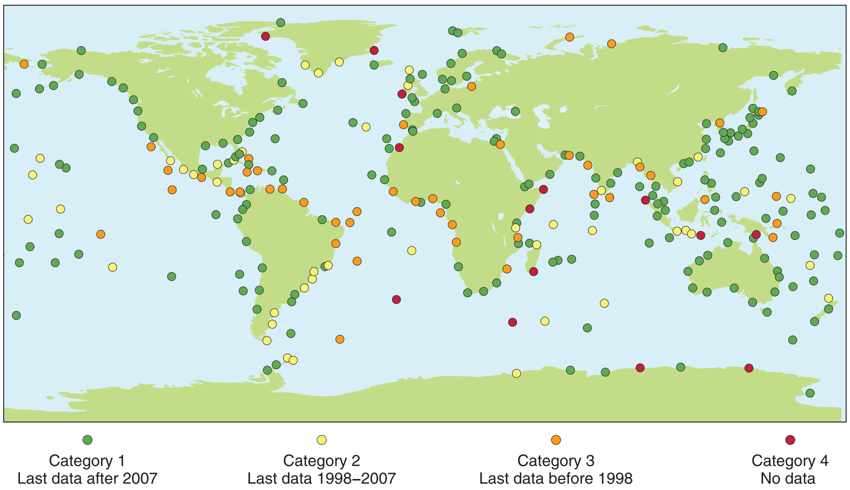

Figure 11. The present status of the GLOSS network of sea level stations showing the status of data delivery from the sea level sites that comprise the Global Core Network. (see http://www.gloss-sealevel.org/)

- All these observing systems are focussed on physical observations but ocean biogeochemistry also plays a key role in the climate system (Chapters 1.1, 5.7, 6.4, 6.5). Though biological and chemical ocean observations have a long history, it is only in the past three decades through programmes such as the JGOFS, IMBER and SOLAS components of the International Geosphere-Biosphere Program (IGBP), that these have been co-ordinated on a global scale and none yet match the density and global scale of physical measurements. The longest timeseries of observations are those made since the 1930s by the continuous plankton recorders towed by research and commercial vessels (http://www.globalcpr.org/) These data have documented the changing patterns of zooplankton distribution many of which can be clearly linked to changes in ocean physics (Reid and Beaugrand, 2012).

In summary, progress over the first decade of the 21st century the *in-situ* observing system (detailed in plenary and community white papers published from OceanObs'09) includes:

- Complete implementation of the core Argo mission with more than 3500 (compared to a target of 3000) floats currently delivering high-quality data from the open and ice free oceans. (It should be noted that there are a number of developments being made that enable profiling floats to collect deeper data and data from ice-covered regions – See Section 3)
- Improvement in global distribution and number of surface drifters for sea surface temperature ground-truthing. (1100 drifters, 470 measuring atmospheric pressure and 700 measuring SST (March 2013))
- Maintenance of Pacific Tropical moored array and extended coverage of the moored array into the Atlantic and Indian Oceans.
- Established a growing network of multidisciplinary moored ocean observatories (OceanSITES).
- The reinvigoration of the science of sea surface temperature (SST) estimation based on the synthesis of the multiple satellite platform data streams and situ data; producing new and better SST products (with errors) via the Global High Resolution SST project (GHRSST).
- Stabilisation of high quality sea level observations under the Global Sea Level Observing System (GLOSS) project.
- The transition of the global XBT network from broad-scale monitoring (taken over by Argo) to circulation monitoring via frequently repeated (FR) and high-density (HD) lines with a global design.
- The success in internationally coordinated efforts to reoccupy a subset of hydrographic and tracer transects (GO-SHIP).

3. Emerging and specialized ocean observing technologies

In the previous section there was a focus on ocean observations within globally co-ordinated observing networks that can be sustained for many years. However, during WOCE, TOGA and CLIVAR oceanographers have also developed and deployed other ocean observing systems, platforms and sensors, some of which may become part of sustained observing systems.

CLIVAR in particular identified three type of observing activities.

- It encouraged and contributed to the establishment of the aforementioned global observing networks in collaboration with GOOS, with the expectation that the data they provided would support ocean analyses and the assessment of ocean variability and change from seasons to decades. Moreover, these data would provide the basis for ocean and climate prediction.
- Secondly CLIVAR sponsored several regional oceanographic experiments designed to test new observing capabilities in pilot mode. Examples are RAPID (monitoring the North Atlantic Meridional Overturning Circulation (MOC)), TACE (in the tropical Atlantic), VOCALS (around South America), SPICE (Southeast Pacific) and KESS (Kuroshio Current extension). Each of these sites, operated for a period of three to five years in regions of particular interest to CLIVAR's research objectives and were instrumented with a mix of traditional and new technologies. The intention was to improve the understanding and representation of a key ocean process in models but also to develop and field-test innovative ocean observing systems that could eventually become part of the sustained ocean observing system. (RAPID is now in its 9th year of observations, e.g. Johns et.al. 2011, and www.noc.soton.ac.uk/rapidmoc/).

- In addition there have been short-term ocean process experiments with ocean observations lasting from a few weeks to two years. These often employed observing technologies that were very likely to be too labor intensive or costly to become part of the sustained system.

Within these last two categories there have been deployments of new, innovative observing systems and sensors that we will now summarize. This is a rapidly developing field and the most appropriate and comprehensive references can be found in the White Papers submitted to the OceanObs'09 conference (Hall, Harrison and Stammer, 2010).

3.1 Advanced observing platforms

An increasing demand for ocean observations, (in particular in remote areas, in winter and under extreme weather conditions), coupled with the high cost of research vessel operations have together stimulated an explosive growth of autonomous ocean observing platforms. Key climate processes occur in the Arctic and Southern Oceans, however sustained ocean observations in multi-year sea-ice, the marginal sea-ice region and under floating ice-sheets have been both a logistical and technological challenge. Modifications to and novel use of existing observations platforms are beginning to fill this data gap. Recent developments to Argo floats, both in software (ice detections algorithm and storage of multiple profiles) and hardware (rugged float bodies and antennae) are now extending the Argo program to the high latitude oceans (e.g. Wong and Riser, 2011). Moored profiling systems deployed on fast- and multi-year ice have also been developed to provided profiles of ocean properties under ice shelves and within the drifting ice pack. (e.g.. Timmerman et al., 2010). Novel use of miniature CTD systems deployed on animals, mainly seals, are now provide ocean observations in the high latitude oceans. (Boehme et al 2008)

Self-propelled ocean gliders, using the same buoyancy engines as Argo floats and, with their short wings and satellite navigation, capable of underwater navigation are now used increasingly to routinely observe ocean property changes (e.g. http://www.ego-network.org). They can navigate the upper ocean (typically upper 1000m) with an effective speed of less than 0.3 ms^{-1}. Most gliders have battery endurance from several weeks up to almost a year depending on profiling depth and sensor suites. Gliders are expected soon to become part of the sustained ocean observing strategy. Other autonomous underwater vehicles (AUVs) include shallow and deep diving systems with propellers. A range of small vehicles with several hour endurance, well suited for coastal and near shore/ship applications, are available. Other systems can sample to 6000 m and have been used to make measurements of bottom boundary layer mixing processes.

New near-surface platforms have been developed. These include large moored platforms with fast satellite communication and significant onboard power capable of supporting new multidisciplinary ocean observatories and complementing regional sea floor cabled installations described below. Other systems use surface wave energy to propel the vehicle (Wave Glider) and unmanned sailing vessels may be expected to become available in the near future.

Consortia of commercial shipping companies and science organizations have come together to arrange for a wide range of instrumentation to be installed on commercial vessels (ferries, cruise ships and container vessels). This expands the capabilities of the Voluntary Observing Ship fleets from previous observations of surface temperature and salinity, meteorological parameters and the deployment of expendable (XBT) probes to include surface layer chlorophyll (fluorescence), pCO_2 and upper ocean velocities. A summary of issues relating to the use of commercial vessels can be found in the final report of OCEANSCOPE project (http://www.scor-int.org/Working_Groups/wg133.htm) co-sponsored by SCOR and IAPSO.

New platforms are under development for use in the near surface environment: Several designs for moored battery-powered winch systems are becoming available that allow sensitive sensor packages to be kept for most of the time below the euphotic and surface layers to reduce bio-fouling and mechanical stress and to profile to the surface when required.

A growing number of cabled sea-floor observatories will enable the deployment of multi-disciplinary oceanographic sensor systems. The relatively high investment cost of sea-cables will limit the number of installations in the foreseeable future, but in particular new sensors and the observation of changes in real time near the sea floor will provide future opportunities for ocean observations. (See http://www.oceanobservatories.org/)

3.2 Specialized observing systems and technologies

Some key ocean parameters (ocean turbulence (mixing) and biogeochemical processes) that are crucial for improved understanding of fundamental ocean dynamics and development of sub-grid scale ocean parameterization in climate models cannot be adequately measured by techniques and observing platforms that are presently commonplace in the sustained observing system.

Ocean turbulence (mixing) occurs sporadically and on short time scales and small spatial scales and so require highly specialized observing platforms. Observations of turbulence near the ocean surface are difficult due to the influence of wave motions, while turbulent observations in the ocean interior are sporadic and weak (Thorpe, 2004). Nevertheless, ocean turbulence is an important parameter in both the surface and deep ocean for dispersal of phytoplankton and stratification, respectively. Direct observations of the turbulence are obtained using fast thermistors and shear probes. These instruments can be fitted to a number of different platforms; free falling (or loosely tethered) profilers; gliders; mooring; submarines and AUV (Thorpe, 2004). Together with complementary observations of the ocean stratification rates of diapycnal mixing can be estimated. The highly episodic nature of significant mixing events put extra demands on the sampling and typically a large number of profiles need to be taken in a region to obtain reliable and representative estimates.

An alternative approach has been to analyze the vertical dispersion of trace elements in the ocean. A particular successful method has been to inject an artificial inert tracer (SF_6 or SF_5CF_3) and follow its vertical and horizontal dispersion over many months to several years and large spatial scale (Ledwell et al., 1993). Several large scale tracer release experiments have been conducted in the Subtropical North Atlantic (NATRE, SaltFinger, GUTRE), Greenland Sea, Deep Brazil Basin (BBTRE) and in the Southern Ocean (DIMES) and have provided estimates of the time and space integrated ocean mixing rates.

Because low frequency sound in the ocean can be detected over great distances and its speed is a function of ocean temperature and pressure, measuring acoustic travel times can be used to reveal the thermal structure of the ocean and its changes over time via a process known as acoustic tomography. The method uses cabled or moored arrays of sound sources and receivers to obtain tomographic images of ocean temperature distributions and their changes. High precision navigation of the moored source and receiver arrays, significant power consumption and potential impacts on marine mammals have so far limited the use of acoustic tomography in a sustained manner (Dushaw et al., 2010).

3.3 New Sensors

In general ocean sensors are required to have low power consumption, to be compact and to have low calibration drift. These requirements assume particular importance when deployment is made on autonomous or expendable platforms and much progress has been made in the past 20 years in improving these properties for temperature and salinity sensors. A diverse range of optical sensors are now available to measure ambient light, reflected light and fluorescence and are also used to measure dissolved oxygen, particulate carbon and chromophoric dissolved organic matter. A growing number of miniature wet chemistry analysis systems and even miniature mass spectrometers are becoming available.

Automatic image analysis and pattern detection will soon allow the routine identification of several types of plankton. First attempts to deploy gene-chips and highly specialized sensors will increase the range of multidisciplinary ocean observations in the coming decade. While the development of such novel biological and chemical sensors, now appears unrelated to the mainstream of climate science, measurements by such sensors may eventually lead to a better understanding of the impacts of climate change on the health and productivity of the oceans.

Robotic platforms, low power electronics and the possibility of small and capable sensors measuring a wide range of physical, chemical and biological parameters will allow for significant enhancements of the present-day sustained ocean observations. At the same time the improvement of ocean modelling capabilities and associated data assimilation techniques described in other chapters of this book will allow use of the full range of complementary *in-situ* and remotely sensed data to provide interpolated ocean information to an increasing range of marine applications. This wider view of ocean observations was a major driver for the OceanObs'09 Conference.

4. Changes in data volume and coverage and implication for synthesis products

The diversity of in-situ observations and the enormous changes over time in their quantity, spatial distribution and precision create difficulties in producing the types of ocean syntheses that are required to assess global scale change in the oceans and to examine the significance of such changes for earth's climate.

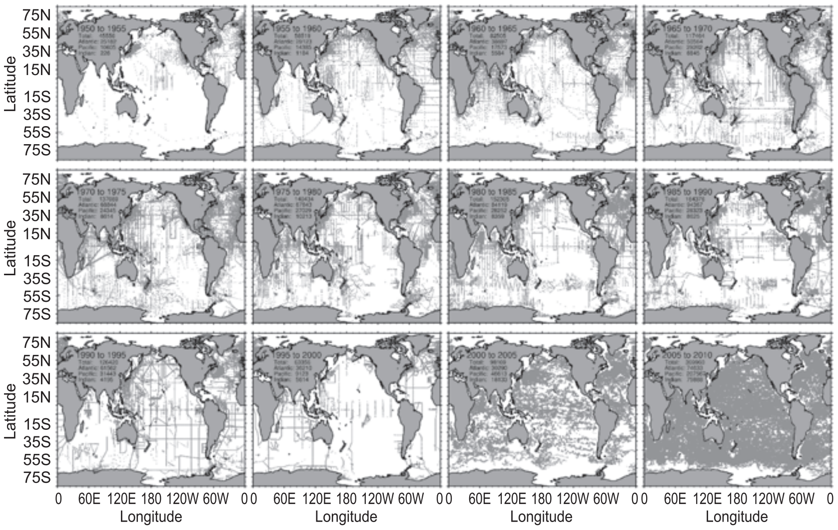

Figure 12. Number of ocean profiles from which data are available in 5 year temporal bins from 1950-1955 to 2005-2010. The increase in profiles in the last 10 years results from Argo..(From Durack, 2011).

Figure 12 from Durack (2011) shows the number and spatial distribution of ocean profile data (measuring salinity) in 5 year time windows from 1950 to 2010. The North Atlantic is the only ocean with reasonable data coverage throughout the entire period – a result of the proximity of many laboratories in Europe and N. America with observational capability and in no small measure due to the long existence of the International Council for the Exploration of the Sea (ICES) (Went, 1972). Until the 1990s the coverage is due in large part to the accumulation of observations made in short-term regional experiments. The WOCE survey of the ocean is clearly visible as long coast-to-coast hydrographic sections between 1990 and 2000 (the WOCE data were collected between 1990 and 1998). For many parts of the central South Pacific, Indian and Southern Oceans WOCE provided the first ever observations of the ocean interior. From 2000 until present, we see the significant impact of Argo, in the first four years during its ramp-up phase that reached 1500 floats in 2004 and its design target of 3000 floats in 2007. Since 2007 no ice-free areas of the deep ocean have been devoid of measurements.

What the figure does not show is that there is also a distinct lack of wintertime observations particularly at high latitude. This results from ship-based operations having been preferentially scheduled in the summer season to avoid weather-related disruptions. This is true even for the relatively well-sampled north Atlantic where in an area bounded by 50-55°N and 35-45°W there are 4 times as many salinity profiles in NOAA's World Ocean Data base in April through September than in the winter months.

The evolution of the observing system has also resulted in significant changes in the depth distribution of observations (Figure 13, based on temperature profile measurements). The dominant data source in the early 1980s was the T4 (450 m) XBTs, these were then supplemented by 750 m (T7) probes and finally, post-2000, by Argo profiles.

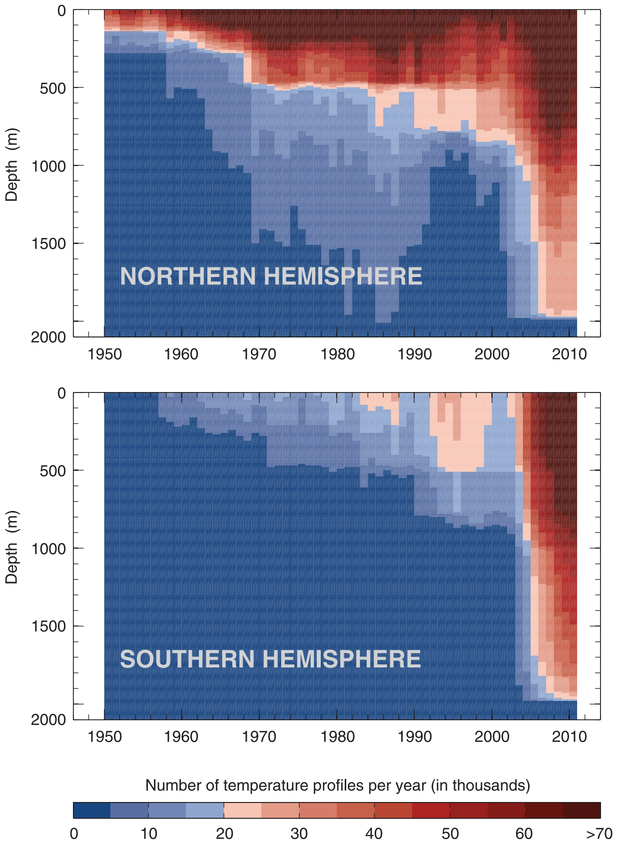

Figure 13. The global number of temperature observations per month as a function of depth based on data from the UK Met Office's (EN3_v2a) data set. (Ingleby and Huddleston, 2007).

While the full operation of the Argo program has led to an enormous increase in ocean observations from the sea-surface to 2000 m, the ocean below 2000 m is still poorly observed (Figure 14).

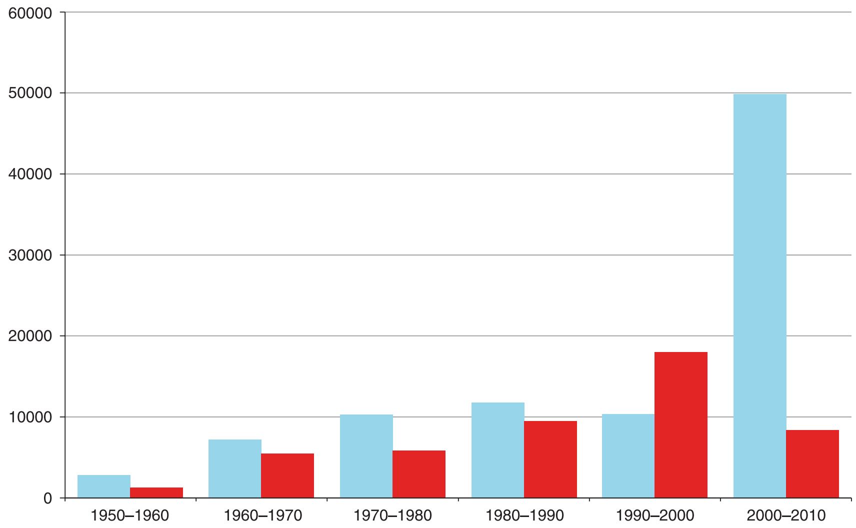

Figure 14. Number of salinity profiles per annum to 1000 m (blue) and to 4000 m per decade (red) in NOAA World Ocean Database.

Here we see that the number of T/S profiles of the upper ocean (here defined as profiles to 1000m) has increased from typically 10,000 per decade to 5 times that number (and with better temporal and spatial distribution) thanks to Argo while the situation for the deep ocean remains poor. With the exception of the decade of the 1990s where WOCE made a deliberate effort to sample the full water column, the number of TS profiles to 4000m remains below 10,000 per decade (~3 per day!).

The fact that the data set of ocean observations is so heterogeneous, (changing since the 1950s from discrete sampling levels, through continuous ship-based profiles to profiles from autonomous instruments and with large areas unsampled for long periods) and with an ever-changing mix of data sources presents enormous challenges to anyone trying to reconstruct the past state of the ocean and to unambiguously determine how that state has changed. For that reason much of what is known about ocean change has come from comparisons of re-occupations of trans-ocean sections (see for example Wong, Bindoff and Church, 1999, Bryden, Longworth and Cunningham, 2005) or from the analysis of ocean time series stations (e.g Joyce and Robbins, 1996). Here it is worth a note of caution. Each observing system element applies calibration and quality assurance before archival of the data. The critical analysis and interpretation of these quality assurance schemes is essential if analysis and interpretation are to be rigorous. The individual observing systems each strive to maximize data quantity and quality while delivering datasets as quickly and efficiently as is practical for each data type. System interoperability in data formats, metadata protocols, and modes of data delivery is clearly an enormous advantage but is not always achieved. There is also a need for data products, for example gridded datasets with uncertainty estimates, in addition to the observational datasets. The documentation and characterization of products and datasets is essential along with guidance on suitability of datasets for a range of applications.

The synthesis and delivery of high-quality data and products for climate applications are major undertakings that have historically been under-resourced. However, the production of these climate-quality observational products is vital for assessing global ocean change and variability, data assimilation model, initialization of climate and ocean only model and for the assessment of these models (See Chapters 5.2, 5.3). As an example, calculations of the global ocean heat content and freshwater (salinity) change over the observational period (Chapters 6.1 and 6.2) are derived from the ocean temperature and salinity data. As we have noted, the temperature record is a synthesis of a number of observation platforms – ship bucket, ship-based CTD, XBT and more recently Argo.

Between 1967 and 2001 the ocean temperature profile data was mainly comprised of XBT data (56%), but since the advent in 2001 of Argo these profiles have increasingly dominated the data record. The comparison of overlapping data sources allows the correction of instrumental shortcomings to be corrected as for example with the fall rate of XBT probes (Cowley et al. 2012).

Aside from the change in observations platform, there has been an evolution of the temperature scale definitions dating back to the early 1900s (Preston-Thomas, 1990) requiring care when considering the smallest temperature changes. Similarly, the methods for the determination of salinity and the definition of salinity have evolved over the observational period (Chapter 3.2).

Ocean data products commonly use the World Ocean Database 09 (WOD09) (Boyer et al., 2009, http://www.nodc.noaa.gov/OC5/WOD09/pr_wod09.html) as their source of ocean observations. The WOD is an initiative of the National Oceanographic Data Center (NODC) and World Data Center for Oceanography (WDC) that collates ocean observations submitted to NODC/WDC by individual scientists and observation programs (i.e. Argo, global XBT, drifter and GO-SHIP), and national and regional data centers. WOD09 provides a centralized quality-controlled database of all ocean observations and metadata by observational platform. This database is used in the production of observational-based, objectively mapped ocean climatologies (e.g. World Ocean Atlas, 2009 (http://www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html) and CSIRO Atlas for Region Seas (http://www.marine.csiro.au/~dunn/cars2009/)). Ocean reanalysis models (e.g. SODA, ECCO-GECCO, and others) combine ocean observational data and an ocean general circulation model driven by known forcing (wind, surface forcing) to reconstruct an ocean climatology that is consistent with the observational record and dynamically balanced. Data assimilation methods recognize that the historical data is sparse and apply a general circulation model to reconstruct the time evolving ocean properties and circulation. Ocean reanalyses are used for short-term (seasonal) to decadal ocean forecasting efforts. Many of these products employ additional data quality control steps further improving the reliability of the database (http://www.icdc.zmaw.de/wohp.html).

Such ocean climatologies are a great help in the documentation of temporal change since they provide baselines against which even sparse data sets may be compared. A recent example of such a comparison is that between the *Challenger* data from the 1870s and the recent Argo climatology (Roemmich, Gould and Gilson, 2012).

5. The Future –outstanding issues and a new framework for global ocean observing

We have explored the evolution of *in-situ* ocean observations and have noted that the rapid advances of the past two decades have brought us to the point where a sustained observing system can be envisaged that largely meets the needs of a wide range of users. Earth's climate has entered a phase in which impacts are increasingly attributable to human activities (sometimes referred to as the anthropocene) and this has greatly increased the socio-economic as well as scientific justification for ocean measurements. Ocean observations have shown that more than 90% of the extra heat energy stored by the Earth in the last 50 years is found in the oceans and that ocean salinity is a direct monitor of the global hydrological cycle (Solomon et al 2007, Durack, 2011). It is, therefore critically important that the observing system is capable of detecting and documenting global climate change so that policy makers (and the general public) can have access to climate observations and products to assess the present state of the ocean, cryosphere, atmosphere, and land and place them in context with the past. To be of both societal and scientific value, these observations need to be sustained over many decades and be of a quality that is adequate to address present-day concerns and those that may be of concern in the future.

Ocean observations are also needed to initialize and evaluate climate models and to improve predictions of climate change. Such assessments are essential for guiding national and international policies that relate to resources (such as fisheries, agriculture and water supply) that are impacted by climate variability and change and efforts aimed at mitigating long-term climate change. The quality of the climate services provided to the public and policy makers is founded on advances in fundamental research for which comprehensive observations are also needed and these go beyond physics to include the mechanisms involved in ocean acidification, ocean deoxygenation and the loss of marine biodiversity. All require globally consistent, regionally coordinated and systematic ocean observations of climate-relevant properties.

In order to guide the development and implementation of the ocean observing system, a framework is required that integrates the present rather independent networks described earlier – Argo, OceanSites, GO-SHIP, XBT, Global Drifter Program, Sea Level (GLOSS). Currently these elements fall under the auspices of several programs each with their own priorities and agendas (Climate Variability and Predictability Experiment (WCRP/CLIVAR), Global Observing System (GOOS) as part of the Global Climate Observing System (GCOS) which is in turn an element of the Global Earth Observing System of Systems (GEOSS)). While all are fundamental elements of the Ocean Observing System (see figure 15 for an artist's view).

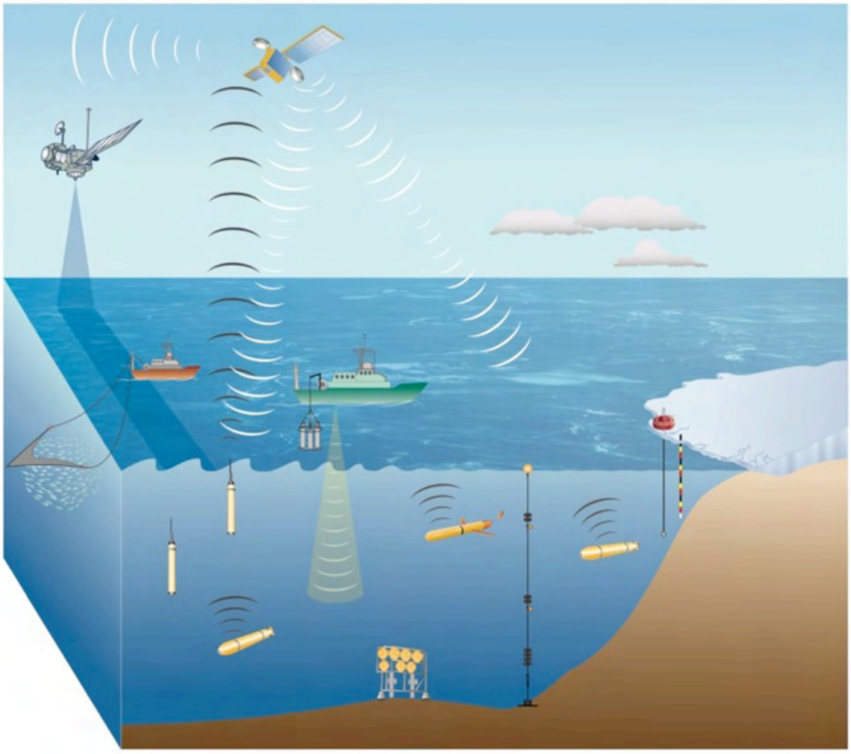

Figure 15. A vision the integrated Ocean Observing system incorporating many different observation platforms to provide the sustained high-quality routine observations of the ocean. (Image from GOOS)

5.1 Building on OceanObs'09

Since the OceanObs'99 conference tremendous progress has been made towards deploying a truly global ocean observing system. Some of the elements of the *in situ* observing system have managed to reach their design specification (Argo and the Global Drifter Program), others still have room for improvement. The status of the present ocean observing system (Figure 16) and community recommendations for its enhancement were reviewed by the OceanObs'09 Conference and related activities were set in place. (Hall, Harrison and Stammer, 2010, http://www.oceanobs09.net/proceedings).

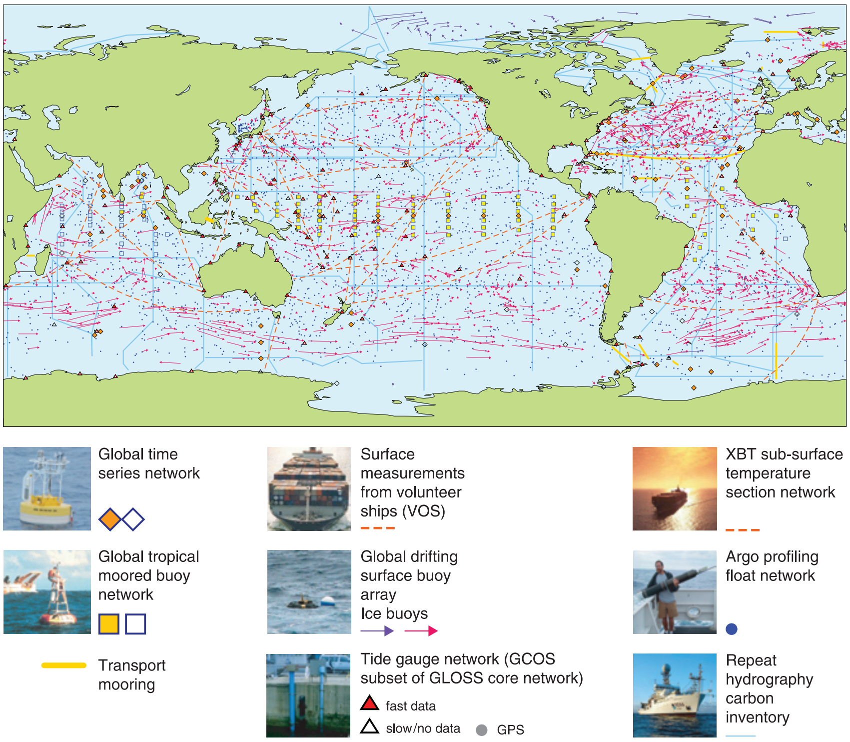

Figure 16. The global ocean observing system is comprised of numerous observing platforms that provide sustained ocean data from the sea surface to the abyssal ocean at varying temporal and spatial resolution. This figure shows the observing system status on May 2013.

Despite some significant inadequacies the present system has allowed us to produce estimates of quantities that are essential for monitoring the oceans' role in climate (heat, freshwater and carbon storage, upper ocean circulation and, with less confidence, changes in the ecological cycle). From these estimates and from our knowledge of the climate system it is now possible to identify a set of Essential Ocean Variables (EOVs). (Table 1) Some of them are already included in the list of the Essential Climate Variables (ECVs) defined by the Global Climate Observing System (World Meteorological Organisation, 2010), while others have to be confirmed and specified in detail. Once the community has agreed to a list, the intention will be for EOVs to be monitored in a sustained and consistent manner and with adequate precision for climate applications. The most cost effective network arrangements have to be determined and financial and governance arrangements have to be developed.

Near surface atmospheric variables Air temperature Precipitation Atmospheric pressure Surface radiation budget Wind speed/direction Water vapour	**Ocean surface variables** Sea surface temperature. Sea surface salinity Sea level Sea state Sea ice coverage Current speed/direction Ocean colour (biological activity) Carbon dioxide (pCO_2)
	Ocean subsurface variables Temperature Salinity Current speed/direction Nutrients Carbon

	Ocean tracers Phytoplankton

Table 1. The subset of the Essential Climate Variables that may comprise the Essential Ocean Variables. Sustained observations of these variables are required for the generation of global climate products.

A key development between the two OceanObs conferences was an emphasis in 2009 on interdisciplinary ocean observations and a call for more effective international coordination and tighter integration between observing activities and the data and information product delivery. In response to the new challenges, a systems approach to ocean observations (Figure 17) was developed and encapsulated in the Framework for Ocean Observing (FOO, http://www.oceanobs09.net/foo/). The FOO concept starts with societal drivers and the demands these generate for ocean observations and include:

- The need to document ocean change (measuring the responses to climate change, overfishing and pollution)
- Initializing ocean models for climate predictions (e.g. El Niño, Tropical Atlantic Variability, Indian Ocean Dipole and their respective impacts on monsoon systems and decadal predictability)
- Initializing short-term ocean forecasts for marine operations (e.g. oil spill and pollution tracking, search-and-rescue)
- Regulatory matters of coastal states (e.g. Climate Change Convention, Convention of Biodiversity, Marine Spatial Planning and associated demands).

The Framework would guide the whole ocean observing community and be organized around a set of “Essential Ocean Variables (EOVs); an approach shown by GCOS to break down barriers to cooperation amongst funding agencies and observing networks.

Implementation would be guided by the level of “readiness” with immediate implementation of components that have already reached maturity while encouraging innovation and capacity building for less mature observation streams and methods.

By taking a systems engineering approach, the FOO input requirements (observations) will be identified as the information needed to address a specific scientific problem or societal issue. The societal issues span from short-timescale needs such as hazard warning to such long-timescale needs as knowledge of ecosystem limits appropriate to the sustainable exploitation of ocean resources. The mechanisms to deliver these observation elements will then be identified in terms of technologies and observing networks. The outputs (data and information products) will consist of the most appropriate syntheses of ocean observation streams to provide services, address scientific problems or permit informed decisions on societal issues.

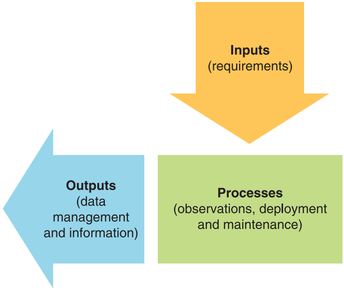

Figure 17. A systems approach to ocean observations, the guiding principle of the Framework for Ocean Observations.

The vastness, remoteness, and harshness of the oceans means that collecting any *in situ* observations is expensive. As a consequence, observing systems have been and will continue to be designed to measure as many variables as possible so as to take full advantage of the limited number of observing platforms. These multiple sensors place demands on energy and thus a focus for FOO will be the avoidance of duplication between observing platforms and networks. However, the complementarity of observing networks (for instance between Argo and ship-based CTD observations) has enormous benefits in allowing intercalibration and eliminating systematic bias. Common standards for data collection and dissemination of EOV data will be adopted so as to maximize the utility of data.

The Framework approach will be used to encourage partnerships between the research and operational communities so as to assess and improve the readiness levels of observation elements and data systems appropriate for each EOV. Similar partnerships will refine requirements. The Framework should also enhance collaboration between developed and developing regions and promote the use of common standards and best practices.

In summary the Framework will promote a more consistent and integrated approach to the assessment of readiness, implementation and setting standards for information sharing among the varied and largely autonomous observing elements. It should also lead to a well-defined set of requirements and goals, facilitate coordination between observing system elements, streamline implementation of sustained global-scale observations by applying a systems engineering approach and identifying best practices.

6. Conclusions

Since the early 1980s and 90s enormous progress has been made in gathering *in situ* ocean observations at global scales that complements information from ocean-focussed earth observing satellites. Building on global-scale research programs and stimulated by the impetus of the 1999 OceanObs Conference, the international community has implemented the first elements of what may become a sustained *in situ* global ocean observing system. Many ocean and climate analysis and forecasting centres are now dependent on measurements and derived products provided by the present observing system. This period of development has coincided with a growing awareness, not only by scientists but by some politicians and a large part of the general public of the need to monitor the oceans in order to quantify the impacts and progress of climate change and of the impacts of pollution and exploitation of the oceans' living resources.

The second OceanObs conference in 2009 built on this progress but also expanded the horizons of systematic ocean observing from its earlier largely physical and science-based perspective to one that recognised the lack of emphasis on systematic biological and biogeochemical observations and that recognised the need to underpin the case for sustained observations by reference to societal drivers.

The coming decade will see a more systematic approach to the sustained observing of the ocean than has been common in the past decades through the developing Framework for Ocean Observations. This Framework has the potential to optimise the assembly of data from multiple and diverse platforms and eventually to optimise observing system design. If we continue to follow the example of the past two decades, innovative observation techniques made possible by experimental technologies will be incorporated into the mainstream of ocean observations.

Of course, any future development, expansion and global-scale implementation of a sustained observing system will require commitment of funds from national and multi-national sources and there will be competition for those funds within the ocean observing community and between the physical, biological and solid-earth science communities. Success in competing for these fund will require a clear demonstration of the benefits, not just to the work of the ocean and climate science communities but also to societal issues such as better predicting the likely progress of sea-level rise and the oceans' role in predictions of seasonal climate.

While our ability to observe the oceans and to understand their role in the earth's climate system have advanced dramatically, national and international oversight structures and funding streams have changed much less – only a slowly growing number of governments or agencies are willing to acknowledge the need for a long-term (~decades) commitment of funds to observing programmes and networks.

While these constraints may hinder progress, the dedication, persistence and innovative nature of the observational marine science community that has already made such remarkable progress might be expected to overcome such obstacles.

The highest priority for the coming decade must be to sustain the present ocean observing system, while improving its coverage and data quality. The system can also be significantly enhanced by the following extensions of existing elements and by integration across elements:

- The sampling domain of autonomous platforms can become truly global through extensions to higher latitude, into marginal seas and the deep ocean, and through higher resolution observations in boundary current regions. Incremental technology developments and definition of new sampling requirements are needed for these extensions.
- Multi-decadal ocean warming and ocean acidification have impacts on marine ecosystems with severe socio-economic consequences. Given the value of ocean ecosystems to human health and welfare, it is important to understand the links between ocean and climate variability, marine chemical process and their impact on marine ecosystems. Thus, there is an urgent need to *fully integrate biogeochemical and biological observations* into the ocean observing system.
- The global network measuring the physical state of the oceans provides a platform for multi-disciplinary observations of biogeochemical and ecosystem impacts of climate change. Key requirements are further developments in low-power sensor accuracy and stability, and effective integration between autonomous and shipboard observational networks (e.g. definition of core variables; ensuring a sufficient quantity of reference-quality data for quality assurance of autonomous sensors).
- Improvements in the observation of the ocean surface layer and of air-sea exchanges require better utilization of research vessels and commercial shipping, improvements to automated measurement systems, better coordination across networks, and a review of sampling requirements for marine meteorology and ocean surface velocity.
- Strong commitment to preserve continuity, or in some cases like satellite measurements of the air-sea momentum flux from scatterometers and variations in the ocean mass field from gravity satellites, reinstate measurement missions. The principal challenge remains to advocate, plan and finance and press for executing the transition of the critical satellite sensors to sustained status.

A major effort is needed to ensure that data quality is maximized, that data access is simplified (including for data types extending across multiple observational networks), and that data products are useful and available. All measurements need to be documented, calibrated and stored in internationally accessible data base systems. Most of the raw data from different observing networks will be combined using a range of techniques from simple statistical tools to full 4DVAR ocean data assimilation (Chapters 5.2 and 5.3) to produce ocean information products that are capable of addressing the user requirements outlined above. This information flow should be implemented by an integrated network of data information centers, data assimilating systems and a number of routine and near real time assessments of key ocean quantities with adequate time and space resolution.

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