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Sustaining observations of the unsteady ocean circulation

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Sustained observations of ocean properties reveal a global warming trend and rising sea levels. These changes have been documented by traditional ship-based measurements of ocean properties, while more recent Argo profiling floats and satellite records permit estimates of ocean changes on a near real-time basis. Through these and newer methods of observing the oceans, scientists are moving from quantifying the 'state of the ocean' to monitoring its variability, and distinguishing the physical processes bringing signals of change. In this article, I will give a brief overview of the UK contributions to the physical oceanographic observations, and the role they have played in the wider global observing systems. While temperature and salinity are the primary measurements of physical oceanography, new transbasin mooring arrays also resolve changes in ocean circulation on daily timescales. Emerging technologies permit routine observations at higher-than-ever spatial resolutions. Following this, I then give a personal perspective on the future of sustained observations. New measurement techniques promise exciting discoveries concerning the role of smaller scales and boundary processes in setting the large-scale ocean circulation and the ocean's role in climate. The challenges now facing the scientific community include sustaining critical observations in the case of funding system changes or shifts in government priorities. These long records will enable a determination of the role and response of the ocean to climate change.

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1. Introduction

Physical oceanography and the circulation of the oceans are central to the study of marine science. Observations form the foundation of our knowledge of the sea. In this article, I give an overview of three primary methods presently in use to make global observations of the state of the oceans, and the UK's contribution to these efforts. While a broad history of the study of the ocean is beyond the scope of this article, I have chosen a few highlights to show how sustained observations have transformed our understanding of ocean physics. A personal perspective on the future of sustained observations and challenges that lie ahead follows. This article was based on a contribution to the Challenger Marine Society meeting on a 'Prospectus for UK marine science and sustained observations' (see also [1], this issue). While some of the great successes of the UK contributions to sustained observations are highlighted, many developments and new insights rely on international collaboration and jointly funded projects. As a consequence, some of the efforts and successes described below will encompass the UK contributions to the wider international effort.

Before beginning a discussion on sustained observations, we must first ask: why are we interested in sustained observations? Here, we take 'sustained observations' to mean long term repeated measurements of the same quantity at the same location. This type of observational approach contrasts primarily with 'process-oriented studies', which tend to consist of a great number of measurements over a limited geographic region and short period of time—often just a few weeks. During the writing of this article, the 5th report of the Intergovernmental Panel on Climate Change (IPCC) was released and has made it increasingly clear that the Earth-Ocean-Atmosphere system is undergoing one of the greatest experiments of our time: that of human-induced change to the climate. The world is getting warmer. Long term changes are clear in global records such as surface air or sea temperatures, sea level rise or carbon dioxide (CO_2) concentration at Mauna Loa (Fig. 1). Reconstructions of global sea level since the late 19th century from *in situ* tide gauges and altimetry are conclusive: sea level is rising and accelerating [2, 3]. In the CO_2 record since the 1950s, while there is evidence of variability on shorter time scales—e.g., a distinct annual cycle—the long term secular trend is unmistakeable. The changes in CO_2 concentration are particularly compelling because increases in CO_2 drive global warming through the greenhouse effect. There is nothing quite as convincing as a long record for climate change.

The discussion in this article is based on the assumption that we are interested in long term sustained observations in order to understand the ocean's role in and response to climate change. However, in the examples given above, for CO_2 concentration and sea level, the ratio of the signal to noise—magnitude of the underlying trend relative to the shorter term variability—is larger than in many other climate records. This type of time series, while forming the cornerstone of the case for human-induced global change, can be misleading for how we understand the ocean. Regional changes may vary in sign; adjustments in circulation may change the distribution of heat around the earth and feedback on the changes, e.g. through the melting of polar ice caps. As we move forward, and as the records of change lengthen, we are addressing questions of why the observed signals have changed. What forcing or interaction caused it? What are the dominant balances in the system? The greatest advances will undoubtedly arise from a combination of observations, theoretical and modelling studies, but the observations will form the core of the new developments.

While there are myriad ways to measure the oceans, both in the array of platforms and sensors available, in choosing observational techniques, two fundamental questions must guide the choice: (1) what are we trying to measure? and (2) how precise do our measurements need to be? In applying these questions, it will become clear that no single observational technique is appropriate for all aims. In addition, while I will focus on advances and challenges in deep-sea sustained physical observations (e.g. temperature, salinity and velocity), any complete ocean observing system will need to be more comprehensive, including biogeochemical and ecosystem components of observations, and from the deep-sea to the shore. The omission of these topics here should not be regarded as indicating their unimportance.

The article is structured as follows. In §2, I will describe three global scale observational methods: ship-based hydrography, altimetry and the Argo profiling float array. In §3, I will highlight the advances made from localised sustained observations. In §4, I will describe four main areas for future advances in sustained observations, and provide a cautionary note towards the newer technologies. Finally, §5 summarises the overall perspective of this article.

2. Sustained global observations

Observations on a global scale have provided evidence that climate change is indeed occurring, and is not just a localised signal of variability. In this section, we will outline methods for making high quality, global-scale measurements and provide examples of some of the understanding that has been derived from them. While observations of the ocean have a rich history, we do not address it here (see e.g. [4]). Instead, we focus on three modern methods still in use today: ship-based hydrographic (temperature and salinity) measurements, satellite estimates of sea surface height, and autonomous profiling floats measuring hydrography. Of these three, it could be argued that the UK has had the greatest role in hydrographic measurements, with the 1870s Challenger expedition in the early days of marine exploration (see also [5] in this issue), and continuing today.

(a) Global-scale, full-depth ship-based measurements: Hydrography

Ship-based hydrographic observations are the "gold-standard" of data quality for measurements of temperature and salinity. The high quality of these measurements arises from pre- and post-cruise calibration of the conductivity-temperature-depth (CTD) sensor in a laboratory, as well as mid-cruise collection of water samples. These water samples are used to independently verify the sensor data against prepared bottles of standard seawater (See [6] for a history of standard seawater). This rigorous attention to the measurement quality, combined with drift-free standards [7], results in the highest accuracy measurements of temperature and salinity.

Until recently, hydrographic observations were concentrated in the northern hemisphere, and primarily in the Atlantic. Organized in the 1980s, the World Ocean Circulation Experiment (WOCE, `http://woce.nodc.noaa.gov/wdiu/`) was a grand international effort to improve the spatial coverage of hydrographic knowledge of the global oceans (Fig. 3). In the WOCE, climate modelling, hydrographic sections and altimetry were gathered together to determine to what extent climate can be predicted, and the extent of man's influence on climate. In setting out the experiment, the hydrographic sections were intended to reduce uncertainties in the ocean's heat and freshwater fluxes. While the originators of WOCE were aware of the variability of the ocean on a wide range of timescales, the need for coverage was key, and snapshots of oceans previously un-sampled, were taken to be representative of that region. This first-ever global coverage of the oceans formed a critical baseline for regions where there were previously no high quality, full-depth observations. The international efforts of hydrography are now coordinated through the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP, `http://www.go-ship.org/`).

The primary downside of global-coverage using hydrographic sections is that making the measurements is resource-intensive. The WOCE experiment took nearly a decade to complete, with multiple global-class ships from participating countries making hydrographic measurements nearly continuously. However, the benefits to this experiment could not have been realised any other way. Slowly varying fields in the ocean can be quantified to high accuracy. Combining the first baseline in the 1990s with repeat observations in the 2000s has yielded remarkable results. The deepest layer of the ocean has been shown to be warming over this time period, with the observed magnitude of warming contributing a non-negligible fraction (roughly

10%) of sea level rise (see Fig. 3) [8]. Without the international cooperation and coordination, these deep warming signals would be occurring unbeknownst to us.

Beyond determining the overall distribution of properties in the ocean, or differencing two repeat measurements to estimate the change, in areas where repeated observations exist at higher frequency, they also show how those properties change with time. As one example in the Atlantic, the UK has led observations at the Ellett and Extended Ellett lines (EL, and EEL, respectively) from Scotland to Rockall (EL), and up to Iceland (EEL), around A24 on Fig. 3. The EL has been occupied regularly since the 1970s. These long term observations have shown that the properties have been experienced warming and salinification across the section (Rockall Trough) since the mid-1990s [9]. Combining the temperature and salinity section data with observations from ocean weather ships places these observations in the context of even longer term variability (since 1948, Fig. 4). Using additional measurements from other repeat sections in the subpolar regions shows that the signal of warm, salty water is penetrating to higher latitudes and towards the Arctic [10].

At the 24°N section across the Atlantic (A5, in Fig. 3), the UK contributed the original hydrographic section in 1957 on RRS *Discovery II*, as well as two repeat sections in 2004 and 2010, with a further repeat planned in 2015. The 2010 section is shown in Fig. 5, where temperatures range from 23°C near the surface to 1.8°C at the bottom. Besides measuring temperature and salinity, hydrographic sections have been used to estimate circulation or current speeds. This is done by calculating density from the temperature and salinity profiles, and applying the thermal wind relation between successive stations. Integrating the vertical shear results in an estimate of transport, which when combined with temperature and salinity properties can further be used to estimate heat and freshwater transport [11]. With a transbasin section such as A5, these methods have been used to estimate the strength of the meridional overturning circulation or MOC [12].

The MOC is the name given to the circulation pattern shown in Fig. 6, where warm salty water moves northward in the surface layers, and then southward in the deep layers, with a conversion from warm to cold occurring at high latitudes. This conversion releases heat to the atmosphere, where it is expected to be one of the processes responsible for keeping the UK warm compared to locations at similar latitudes of North America. Combining the transbasin transport with surface wind-driven Ekman transport and Gulf Stream transport through the Straits of Florida provides an estimate of the MOC. This was done in 2005 using five hydrographic sections [12]. The estimates from 1957–2004 showed a worrisome 30% decrease in the strength of the overturning circulation from 22.9 Sv (1 Sv = 10^6 $m^3 s^{-1}$) in 1957 to 14.8 Sv in 2004 (Fig. 5). The strength of the MOC is directly related to the strength of the heat transport [13], and a shutdown of the MOC has been associated with a cooling over the UK and Europe. We will return to the discussion of the MOC changes in a later section.

In high-latitudes regions (the Arctic and around Antarctica), data coverage is relatively sparse as compared to the wider North Atlantic. The UK has led recent efforts to synthesise Arctic measurements from multiple countries, creating the first circum-Arctic budget of net inflows and outflows [14]. In the Southern Ocean, the UK was a key contributor to the SASSI (Synoptic Antarctic Shelf-Slope Interactions) programme which coordinated synoptic sections all around Antarctica for the first time [15]. The Drake Passage sections (A21/S1 on Fig. 3) across a narro choke-point of the Antarctic Circumpolar Current (ACC) have now been occupied for nearly 20 years, and are one of the UK's outstanding contributions to global hydrographic efforts. These observations have resulted in several scientific breakthroughs recently outlined in a review paper [16] (see also [17], this issue). These include a quantification of the ACC structure and transport, increased understanding for the stability of transport on interannual timescales, and determining the mechanisms driving changes in the overturning in the Southern Ocean.

(b) Global-scale measurements of variability: Satellite altimetry

Satellite-derived estimates of sea level also give a global view of the oceans. Unlike hydrography, where repeats are annual to decadal, present-day satellite estimates of sea level are made globally every 10-days or better. However, they provide a surface-only view of the oceans, while hydrography can measure depth-variations as well. Satellite altimeters on American, European (including the UK-led CryoSat) and other satellites measure variations in sea surface height relative to a reference ellipsoid. The use of satellites to estimate ocean circulation came into focus with the launch of TOPEX/Poseidon in 1992. While altimetry had been used for a few decades prior to measure sea surface height, TOPEX/Poseidon was the first mission specifically designed for high-accuracy estimates of the large-scale ocean surface circulation from spatial gradients in sea level. Figure 7 shows sea surface height anomaly (conventionally expressed relative to a multi-year mean sea surface) from TOPEX/Poseidon altimeter in August 1996.

Using multiple satellites together—the precise TOPEX/Poseidon with the more highly resolved, but less precise, ERS-1—provides a new view of the oceans. Figure 7 shows the combination of the two for the same period as (a). Combining two altimeters with different designs, provided an unprecedented view of the smaller horizontal scales (50–200 km) in sea surface height: the ocean mesoscale [18]. The impression is almost that of acquiring new spectacles with which to view the ocean. The altimeter data showed that the energy in the ocean mesoscale was enormous (13 exajoules, 1 exajoule= 10^18 J) which is more than half of the "general circulation" budget (20 exajoules) [19]. Recent reviews have expounded on the revelations of ocean mesoscale field provided by altimetry, and will not be repeated here [20, 21].

The mean sea surface height field is somewhat more complicated to extract. Oceanographers are interested in the height of the sea level relative to the geoid—the regionally-varying distribution of sea level associated with an ocean at rest—since the difference (dynamic topography) is the portion of sea level associated with circulation. With the advent of the GRACE (Gravity Recovery and Climate Experiment, 2002–present) and GOCE (Gravity field and steady-state Ocean Circulation Explorer, 2009–2013) missions, it is now possible to estimate the geoid more directly [22] (see also [23], this issue).

(c) Global-scale measurements of variability: Profiling floats

Argo profiling floats are self-contained measurement platforms which drift with the currents making measurements and then transmitting them to base stations on land. The floats are designed to control their buoyancy to "park" at 1000 or 1500 m deep for 10 days, then adjust their volume to sink to 2000 m deep, and then rise to the surface while measuring temperature and salinity. At the surface, the floats then send their data via the Argos (or, more recently Iridium) satellite data network, before sinking to their parking depth once more [24]. Their unique sampling pattern allows global measurements, but restricted to the top 2000 m and away from boundaries.

The internationally-coordinated Argo profiling float programme was implemented in the early 2000s. The complete Argo network was proposed to contain over 3000 floats, each profiling once every 10 days to 2000 m. This aim was achieved in Nov 2009. Fig. 8 gives a view of the coverage at present. With the design coverage and repeat frequency, the global ocean temperature and salinity is measured at roughly $3{\times}3^{\circ}$ resolution. While individual profiles sample every 10-days, the nominal temporal resolution of the data is a coarser 3-monthly timescale, due to the limited spatial coverage. In the North Atlantic, the coverage greatly increases the spatial and temporal resolution, compared to previous hydrographic sections, but in the Southern Ocean the difference has been even more remarkable [25].

One of the benefits of the Argo network over traditional hydrographic measurements is that it samples continuously. This means that after a remarkable atmospheric or oceanic event has occurred, the data can be used retrospectively to quantify and understand it. As an example, during the 2009/10 and 2010/11 winters, the atmosphere was in a strongly negative North Atlantic Oscillation (NAO) state. Sea surface waters during the wintertime NAO were anomalously cooler. To investigate the temperature anomalies associated with the repeat NAO, Argo floats were used to determine that the surface temperature anomalies were due to the re-emergence of subsurface anomalies created during the first negative NAO [26]. These results then hint at a controlling role for the ocean in atmospheric circulation patterns. With traditional observational methods, and the lack of predictability of the NAO, it would not otherwise have been possible to study this effect.

There are some inherent difficulties in distributed networks of expendable platforms. One of the primary issues for climate-quality time series is that of data quality. Unlike ship-based hydrography, the CTD sensors used on Argo floats are not calibrated at the end-of-life of an Argo float. Since floats are designed to last four or more years, the sensor is subject to drift due to degradation by physical effects or biological fouling (when organisms from bacteria to barnacles take up residence on the floats). In addition, given the size of the array and the contributions from multiple countries, inter-calibration and quality control of float data is managed separately by each country and sometimes multiple groups within a country. An individual scientist may be responsible for the quality control of the portfolio of floats deployed by his or her group or country, and use those floats and available hydrographic data to inter-calibrate sensors. Depending on the size of the portfolio, the manufacturer of floats in the portfolio and possibly somewhat subjective calibration choices, Argo data drift may not be adequately corrected, or may even be over-corrected. An additional difficulty is that of using an irregular dataset. To combat this difficulty, the UK Met Office has created a publicly-available, quality-controlled, spatially and temporally-gridded datasets using both Argo float profiles and hydrographic data from the world's oceans [27].

Summary

These three global-scale sustained observations of the world oceans have led to significant gains in our understanding of the state of the oceans. Returning to our overriding questions of what we are trying to measure and how precise the measurement needs to be made, it becomes clear that at present, only ship-based hydrographic with frequently calibrated sensors, and comparisons against drift-free standards, give the highest-precision, climate-quality data. With these measurements, small changes in the deepest layers of the ocean are discernible, while at critical choke-point locations across narrow passages in the North Atlantic or Southern Ocean, repeated measurements allow a study of the temporal variability in changes. However, where temporal changes occur over broad scales, ship-based hydrography may not be an efficient use of resources. Instead, Argo float profiles provide repeated measurements, at coarser and distributed resolution while satellite-derived sea level profiles a global view of the surface-only circulation.

Combining the three observational datasets (hydrography, altimetry and floats) allows additional uses of the data. Data assimilation programmes, whereby dynamically-plausible numerical simulations of the ocean use observations to adjust the properties to match observations, provide global, repeated estimates of the state of the ocean. These state estimates are coordinated through Global Ocean Data Assimilation Experiment (GODAE) and Estimating the Circulation and Climate of the Ocean (ECCO) [28] and were one of the original goals of the WOCE programme. They are now one of the crowning achievements of the altimetry-Argo synergy [21]. The use of observations in ocean modelling efforts are discussed further in [29], this issue.

3. Localised sustained observations

In the introduction, we identified that documenting and understanding climate change is one of the primary motivations for sustained observations. Due to the global nature of climate change, the focus of the previous section was on global-scale observations which allow an estimate of how widespread the signal of change is. However, ship-based hydrography rarely resolves changes on short timescales; altimetric measurements retrieve information from the sea surface only; and Argo floats capture the coarse spatial variations in the top 2000 m, away from ocean boundaries. Present and future advances will rely on the ability to resolve the process of change, which models suggest will be quite rapid (on the order of months) [30, 31].

Localised measurements (fixed point time series) with frequent temporal sampling have proven useful to climate studies already. In the atmosphere, single point measurements, e.g.

the Mauna Loa CO_2 (Fig. 1), is a good indicator of the variations of CO_2 in the atmosphere, and thus provides a record of CO_2 variability from sub-annual to decadal timescales. In the ocean, frequently repeated stations were occupied by ocean weather ships (1945–2009), at several sites agreed internationally in 1946 [32]. Present single-point observations include the Hawaiian Ocean Time Series (HOTS), Bermuda-Atlantic Time Series (BATS) (see also [33], this issue), the Rothera Oceanographic and Biological Time Series (RaTS) and Porcupine Abyssal Plain (PAP) sites (the latter two being UK-led). However, the representativeness of the Mauna Loa record for variations in CO_2 results from the relatively short timescales of stirring and homogenisation of the atmosphere. In contrast, in the ocean, single point measurements are less likely to be good indicators of global sea level rise or warming. What they provide, when used at key locations, is the ability to detect events, quantify change or observe regime shifts, without the dangers of temporal aliasing that are intrinsic to less frequent observations.

Here, I focus on two examples of localised observations: the joint UK/US RAPID array at 26°N in the Atlantic and a new autonomous platform type, the autonomous underwater vehicle (AUV). The RAPID programme is an example of a moored observational programme to study large-scale ocean circulation. It has been operating since 2004 and is presently funded through 2020. AUVs of which one type is the underwater glider, provide new potential for sustained observations, though they are still an emerging technology.

(a) Moored arrays

While moored observations have been around for over a century, the focus here will be on using them to understand large-scale changes in ocean circulation. A mooring array is a platform for anchoring sensors to the sea bed. It consists of the anchor, a wire or rope (to which the sensors are attached) and flotation to keep the wire upright. In this way, a vertical profile of data can be measured at a fixed location, with relatively high temporal sampling. Moorings can have a surface expression (buoys or instruments above the surface of the water), but these are costly and can add an element of risk. (Surface waters and waves are rougher, and instruments or equipment on the surface is at risk to ships travelling in the area.) Moorings without a surface expression are unable to transmit their data back to base stations, but must be recovered (using a research ship) in order for data to be downloaded from the sensor packages. While subsurface moorings are less risky, they can still be damaged by fishing or when strong currents knock-down the flotation which may then be damaged by pressure, preventing recovery of the data.

Moored arrays have been critical for our understanding of ocean dynamics. In the Pacific, the TAO/TRITON (previously TOGA/TAO) array has revolutionised our understanding of El Niño and allowed predictive capability of this globally-important phenomenon [34]. In the Atlantic, the UK has led the installation of, and analysis of observations from the RAPID subsurface mooring array at 26°N. This array is to capture the strength and variability of the MOC and has now produced an 8.5 year record (starting in April 2004) of the MOC. Results from this dataset have revolutionised our view of the variability of the MOC.

The RAPID array measures the MOC at temporal resolution of about 10-days (Fig. 9) [35]. While hydrographic estimates suggested a long term slowdown of this circulation from 22.9 to 14.8 Sv over the period 1957–2004 [12], the first year of RAPID measurements demonstrated that the short time-scale variability of the MOC swamps the apparent signal of decrease identified from infrequent hydrographic measurements [36]. Unlike the two timeseries in Fig. 1 and 2, where five measurements over the span of observations would likely recover the right sense and similar magnitude of the trend in properties, the MOC variations on short timescales prevents a similar approach from hydrographic measurements.

With each extension to the length of the time series, new physics and variability emerge as longer timescales are resolved. After 4 years, a seasonal cycle began to emerge with an unanticipated range of 6.7 Sv [37]. When 7 years were accumulated (2004–2011), a remarkable weakening of the MOC was documented [38]. This weakening was about 30% of the magnitude of the mean, similar to the change observed from hydrographic sections, but it persisted for over a year. With the present record at 8.5 years, interannual variability of the MOC is evident, with a decline an order of magnitude faster than that shown in IPCC models [39]. Using the RAPID time series of the MOC alongside the Met Office estimate of ocean heat content [27], the impact of the recent slowdown of the MOC can be seen on the large-scale properties of the ocean. The decline between Apr 2009–Mar 2010 was associated with a striking decrease in meridional heat transport, and a cooling of the subtropical North Atlantic between 26 and 41°N in the top 2000 m [40].

Besides directly contributing to our understanding of ocean circulation and dynamics, the RAPID time series is also a benchmark for ocean modelling [29]. Models now show mean strengths of the overturning transport in reasonable agreement with the RAPID time series, with some capturing the variability of the seasonal cycle as well. The recent downturn in the MOC observed by RAPID was harder to simulate, however, with models typically only showing only half the observed decrease [38]. More recent evidence suggests that the downturn may be driven by fluctuations in the atmosphere [41]. For a record of change, localised observations such as the RAPID array have made clear that the oceanic processes fill the range of timescales from daily to decadal.

(b) Autonomous underwater vehicles

Autonomous underwater vehicles provide new potential for sustained observations. Unlike Argo floats, they can control their position (barring exceeedingly strong ocean currents) and unlike typical subsurface mooring arrays, can transmit their data in near real-time to scientists in their laboratories. There are several types of autonomous underwater vehicles (AUV) currently in operation. The larger UK-developed Autosub-class of platforms can support higher power sensors and has remarkable under-ice capabilities [42]. At present, however, it requires ship support and has deployment durations on the order of days. New developments within the UK Marine Autonomous and Robotic Systems group will permit longer deployments. Here, I will focus on a second type of AUV, the underwater glider, which has demonstrated potential for sustained observations. These gliders were envisioned by oceanography pioneer Henry Stommel in 1989 in a futuristic view of ocean observations [43]. In it, he imagined a future for oceanography, where the 48 hydrographic sections of WOCE could be occupied monthly by underwater gliders. As an example, he anticipated 10 gliders being used for the 24°N (A5) hydrographic section in the Atlantic, crossing back and forth, with pairs of gliders coming together for inter calibration. The repeat of this section in 2010 required over a month on a research vessel, with associated costs in fuel, crew, technician and scientist time, as well as measurement expenses. Some twenty years later, gliders are now capable of profiling to 1000 m, for missions of 6 months and longer, recovering 1000 or more profiles of temperature and salinity from a single glider. They can be controlled remotely, linking up via satellite telephone each time they surface, to transmit their data or be redirected to another target position.

Gliders have several advantages relative to other measurement techniques, however when used in isolation, the data can present challenges in their use. Gliders are inexpensive when compared to operating costs of global-class research ships. Unlike Argo floats, gliders are designed to be recovered after a mission, allowing for recalibration of sensors. Gliders have also proven themselves in extreme conditions. In the Southern Ocean, gliders were deployed from the ice shelf (Fig. 10) and sampled in a local, ice-free area or polynya [44]. In the Labrador Sea, where intense winter storms result in deep water formation, two gliders made over 1200 profiles in six months [45]. However, while a hydrographic section recovers a full transect in a month, and the Argo array creates a global snapshot every couple of months, gliders travel slowly through the ocean in a narrow region. The slow speed (about 0.5 knots or 0.2 m/s) is dictated by power requirements and is necessary to extend their duration. Variations associated with internal tides or waves can be aliased into individual profiles of data [46], while seasonal changes can be aliased into spatial variations [47]. Combining glider data sets with other data, such as from satellites, may ameliorate some of these problems (Fig. 11). A satellite data field can provide insight into the spatial variations in a region, while the the glider gives a window into the subsurface region.

As an emerging technology, gliders are presently a risky measurement technique. While gliders are designed to last longer than 6-months for a single mission, and the current record is around 11 months, a recent analysis of UK and European glider missions showed that a glider deployed for a 90 days has a 50% chance of failure within the first 90-days [48]. While there is a risk of loss for any instrument deployed into the ocean, the pattern of glider deployment, with time spent on the surface communicating with satellites means that they can be damaged by passing ships. They are also relatively complicated instruments, with several moving parts, and are subjected to enormous changes in pressure as they profile continuously between the surface and 1000 m. These stresses can damage the glider, causing leaks or other problems, sometimes thousands of kilometres from land.

Summary

Two methods for localised sustained observations were presented. For moored observations, the example highlighted was the UK-led RAPID measurements of the MOC and advances they have provided to our understanding of ocean circulation. The second is an emerging techology of underwater gliders, with potential yet to be fully-realised. As with global-scale observational methods, each of these measurement methods has advantages and disadvantages which must be considered before using them. While both offer the potential for high quality data, they present trade-offs in their sampling strategies (moorings fixed in space but with high temporal sampling; gliders moving slowly through space and time). In addition, the varying levels of risk associated with each, with relatively high risk for gliders at present means that they must be used with caution if the aim is to provide a high-quality, continuous observation.

4. Future of sustained observations

In just the past two decades, the methodologies with which we observe the ocean have changed dramatically. No longer restricted to ship-based measurements, we now routinely use satellite and autonomous float data, while moored observations are now being used to examine basin-wide changes in ocean circulation. These networks of satellites and autonomous platforms have multiplied the number of observations we can make, while combinations of data types have yielded new insights. The amount data now being retrieved would not have been possible from ships alone. In the following, four areas for development will be highlighted. Three of them are about pushing the limits of some of the current measurement techniques: (a) geographically, (b) giving a wider-view and (c) shrinking the scales that are observed repeatedly. The fourth (d) is about pushing our limits in developing practices and methods to exploit the strengths of individual datasets, and the synergies between them. However, in considering the brave new world of observational methods, extreme caution must be applied before considering abandoning traditional measurement techniques. These issues are discussed in (e).

(a) Deep ocean, marginal seas and under-ice measurements

One of the most straightforward improvements to our observational methods will be to extend them to areas where coverage is sparse. As noted above, Argo floats only measure the top 2000 m in water and away from boundaries. New measurements will extend both to the deep ocean (below 2000 m) and to the marginal seas (regions between 0–2000 m deep), and will need to address the challenges associated with each [49]. The deep ocean observations are critical for estimating decadal changes in Earth's radiation balance [50], but are currently limited to ship-based hydrography. Several prototypes for deep Argo exist, and the first few deep floats have been added to the UK Argo fleet. However, as a recent technological development, their reliability and endurance is not yet proven. In addition, measurements under ice in the Arctic or around Antarctica are sought, to shed light on the accelerated rates of melting in both oceans. Under-ice observations have been made by Seagliders, Autosub [42] and profiling floats [51]. Challenges associated with lack of communication (no access to the surface) and impacts from ice have been addressed by adding sonar communications, creating more robust float bodies or adding ice-avoidance algorithms.

(b) A wider view of circulation

The RAPID programme has demonstrated both that it is possible to measure the basinwide circulation on short timescales, and from these observations have shown that the MOC at 26°N is highly variable on all observed timescales. We now question whether measurements of the MOC at a single latitude are representative of the global overturning. Several arrays around 40°N in the Atlantic indicate that variability is regionally similar, but the relationship with 26°N is less transparent [52]. Modelling studies suggest a break in coherence at the interface of the subtropical and subpolar gyres (Fig. 12) [53].

The pioneering work of the RAPID programme has led to new developments in observing the ocean circulation. A new basin-wide observational array is set to be deployed in 2014 to observe the overturning in the subpolar North Atlantic (Overturning in the Subpolar North Atlantic Program, OSNAP) [54]. The UK-contribution to OSNAP builds both on the expertise developed through RAPID and from previous array deployments at Cape Farewell, Greenland, where the deep western boundary current was measured [55, 56]. The aim of the programme is to quantify heat and freshwater fluxes around the subpolar gyre, from the Labrador Sea to Cape Farewell, to Scotland. It is expected that observed changes “downstream” at 26°N may be related to adjustment processes at higher latitudes such as deep convection anomalies. Through the two arrays, RAPID and OSNAP, we will have a better understanding of the Atlantic meridional overturning circulation. A third array is still in early stages of deployment in the South Atlantic (South Atlantic Meridional Overturning Circulation, SAMOC) [57]. This transport estimate at the southern boundary of the Atlantic will give a view of what is entering and leaving the South Atlantic from other ocean basins, completing the picture. Without the work of RAPID, this new observing system to measure ocean circulation from north to south in the Atlantic was inconceivable.

(c) Shrinking scales

At the same time that we are looking at connectivity across entire ocean basins, we are also shrinking the scales at which we make sustained observations of the oceans. Just as the addition of a high-precision altimeter shifted our view of the ocean to reveal the ocean mesoscale (50–200 km, Fig. 7), new methods both from space and *in situ* are materialising. Wide-swath altimetry (Fig. 13) will allow sea surface height observations of the ocean *sub*-mesoscale (1–10 km features within a 130 km swath) [58]. While Argo floats contribute a much-needed subsurface view to complement present-day altimetry, gliders are likely to reveal high-resolution vertical and horizontal scales to complement swath altimetry. New techniques to measure mixing from autonomous platforms (directly from gliders, [59] or from microstructure instruments installed on them) and moorings (from high frequency velocimeters) promise new insights into the temporal variability of the smallest scale physics of the ocean.

Though this article initially focused on large-scale sustained observations for the study of climate change, numerical simulations of ocean circulation have shown that processes at the smallest scales critically influence the large-scale circulation [60]. Those smallest scales of oceanic processes—from centimeters to kilometers—are too small to be directly simulated in climate models with grid sizes ranging from a quarter degree (roughly 25 km) and larger. Instead, they are represented by simpler parameterizations. The particular implementation or choice of parameterization can result in drastically different structure of even the time-average, large-scale ocean circulation [61].

(d) New methodologies and synergistic analyses

This last highlight for the future of sustained observations is more about pushing our limits than those of the instruments. Combinations of different data sources can provide a more complete picture of the ocean by capitalising on the complementary nature of various platforms. The depth coverage of Argo supplements the spatial and temporal resolution of altimetry. Eulerian time series from moorings complement the slowly profiling, but high vertical resolution of glider data [49], while the spatial evolution from satellite data compensates for the slow translational speeds of gliders [46, 62]. In a hybrid between point measurements and spatial coverage, a recent experiment used gliders to analyse the ocean from a Lagrangian frame of reference. Lagrangian floats, i.e. floats which follow the motion of fluid parcels, were deployed and then circled by gliders. The floats accounted for the background advective field, while the gliders created a small scale view of spatial variations around the parcel of water (Fig. 14) [63]. Combining satellite altimetry with the Global Drifter Program (`http://www.aoml.noaa.gov/phod/dac/index.php`) permits high quality estimates of surface currents [64]. Using this same dataset, new statistical techniques are being developed through collaborations between oceanographers and statisticians to deal with distributed networks of observations [65]. These new methods promise to deliver greater understanding of surface processes of the ocean, such as the eddying activity associated with jets or currents in the ocean (Fig. 15). Integrating measurements in new ways, rather than just bin-averaging or comparing observations made in the same place and time, will allow us to maximise the use of datasets already in hand.

(e) A cautionary note on new technologies for sustained observations

While the development of autonomous and remotely operated systems provides new methods and results, it also brings with it new challenges. Can autonomous vehicles and floats replace ships? The answer is certainly “not yet”. Quality control of data from autonomous systems is not yet mature. For Argo floats, the calibration and inter-calibration is subject to human guidance and, perhaps, error. By the design of the system, floats do not undergo the same kinds of rigorous calibration that is applied to ship-based hydrography. For glider data, while rapid improvements to data processing are underway, procedures are also not automatic. With large numbers of floats or gliders, the calibration problem will become both simpler (more instruments to intercompare) and more difficult (more data to handle). Reliability of autonomous platforms is also underperforming the intended capability. The probability of a deep glider (1000 m profile) aborting a 90-day mission is 0.5 [48], limiting their use for sustained observations. In addition, piloting choices can affect data quality, necessitating good communication between pilots and the data end-users, which is not always the current practice. While sensors for measuring temperature and, to a lesser degree, salinity, are high quality and relatively drift-free when compared to biological and chemical measurements, even a small drift can be disastrous for climate-quality time series of ocean properties.

A recently discussed example comes from the use of expendable bathythermographs or XBTs for ocean heat content estimates. XBTs make temperature profiles by measuring temperature as a function of time. If the instrument has a known fall-rate, then the time can be converted to pressure. However, manufacturing changes in the 1960s and 1970s resulted in an apparent warm “bump” in the globally-averaged temperatures between 1970–1985 (Fig. 16). Rather than the warming being caused by a widespread change in temperatures, it was attributed to a large number of XBTs having a fall rate different than expected [66]. The result was an error in the global time series of heat content.

Will autonomous vehicles and floats eventually replace research ships? I do not think they can. For the purposes of measuring the broad-scale properties in the oceans, Argo floats work reasonably well. With a large array (over 3000 floats), modest resolution requirements (300 km resolution at 3-monthly timescale), and continuous replenishment, the loss of an individual float does not significantly damage the data quality of the network overall. The transbasin arrays such as RAPID at 26°N require specialised equipment and experience, provided by our research ships, to deploy. Replacing the boundary moorings with autonomous underwater vehicles would be risky in critical locations. For the gliders to prioritise endurance (presently deployed moorings are only recovered after 18 months of sampling), their speed would have to be limited. Limiting the speed of the glider means that in boundary currents, they will struggle to maintain position. In addition, because they must surface to determine their position and transmit data, gliders become susceptible to boat traffic. As such, they are inherently riskier than subsurface moorings, particularly when used near shore where traffic is intensified. How willing are we to suffer the loss of a month or several months of measurements due to a failure of a critical instrument? While new technologies offer exciting possibilities, the choice of a particular observational technique must be guided by the scientific question, the necessity for precision, and reliability.

5. Conclusions

The UK oceanographic community has both led and contributed to sustained observations of the oceans. Hydrographic sections provide high quality temperature and salinity measurements to the deepest depths of the ocean. Satellite altimeters provide weekly estimates of sea surface height, from which surface currents can be derived. Argo profiling floats make continuous, near real-time measurements of the top 2000 m of the oceans. Taken together, these observations give a global picture of the state of the oceans. The present and future observations of oceanography will be in measuring the large-scale, time-varying ocean circulation. Transbasin mooring arrays, beginning with the RAPID array at 26°N in the Atlantic now provide continuous estimates of the meridional overturning circulation, resolving variability on timescales of days to years. Each of the different platforms—ships, satellites, floats, moorings and gliders—has afforded new insights into the physics of the oceans, with the latter four highlighting the unsteady nature of the ocean circulation.

The future of sustained observations has four areas prime for development. (1) In new technological capabilities, increasing the ability of autonomous systems to measure in the deep ocean, marginal seas, and under-ice is already underway. (2) Widening the lens with which we view the Atlantic overturning circulation, the RAPID array at 26°N will soon be joined by the OSNAP array in the subpolar North Atlantic, allowing us both to monitor the changes to the circulation, and pose new questions as to how the observed changes are arising and interconnectivity of circulation. (3) While the focus here has been on climate scale processes, numerical model studies have shown that the largest scales of circulation depend critically on the smallest scales parameterised, that is, on ocean mixing. Presently, measurements of mixing are largely confined to process-oriented studies: short duration and limited spatial scope. New technologies will permit mixing scales to be observed continuously, allowing investigation of their temporal and spatial variability, enabling new and better parameterisations for ocean models. Finally, (4) as the types and sources of data are increasing, so too are the opportunities to combine data in innovative ways. In this way, deficiencies in one datatype can be compensated for by strengths in another. New statistical techniques will need to be developed to deal with distributed networks of data, e.g. from Argo profiling floats. The promise of new technologies is great, but for a given application, the science-aims must drive the choice of observational method.

In order for the measurements already taking place to have maximum impact, they must be sustained so that their observed changes can be placed in the context of natural variability. Indeed, the longest records we have will be the ones that were started a decade or a century ago. One of the greatest challenges of sustaining observations for marine science is their expense. International coordination of efforts, such as GO-SHIP for hydrographic sections and EuroArgo (www.euro-argo.eu) programme for profiling floats has helped to distribute the costs between countries. The RAPID project, while UK-led, was jointly funded by the US National Science Foundation and National Oceanic and Atmospheric Administration (NOAA). However, in the UK there is currently no funding body for long term sustained observations in physical oceanography. Without such funding, sustaining long records requires continuous appeals for follow-on funding [67]. Political shifts, changes in government priorities or science funding systems can inject uncertainty into the future of sustained observations. Gaps in long records can have dramatic consequences for statistical methods to determine trends or changes, meaning that even a short gap could negatively impact one's ability to identify change [68]. While in the US, the NOAA funds certain routine observations, there is as yet no mechanism in the UK to ensure the integrity of sustained observations.

Climate change is not a problem that will be solved in the next 5 to 10 years. It is ongoing and continuously changing. We are pushing forward, extending the technological capabilities, and incorporating new theoretical understanding into our analysis of data and design of experiments. As time series are built up, and records lengthen, we will be able to discern the complex relationships between the ocean circulation, its forcings and effects. While climate change is a certainty, the regional changes and feedbacks are not yet known. The need for sustained observations to document and understand processes responsible for climate change is critical.

Acknowledgment

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6. Figures & Tables

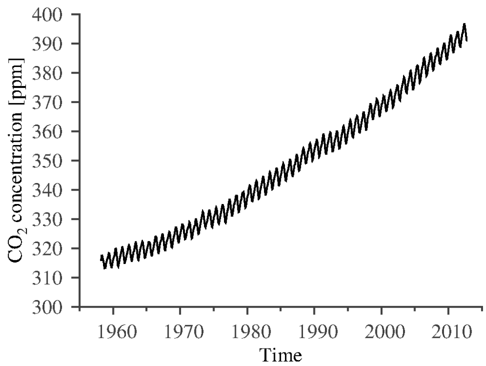

Figure 1. The "Keeling curve" of carbon dioxide concentration on Mauna Loa, Hawaii.

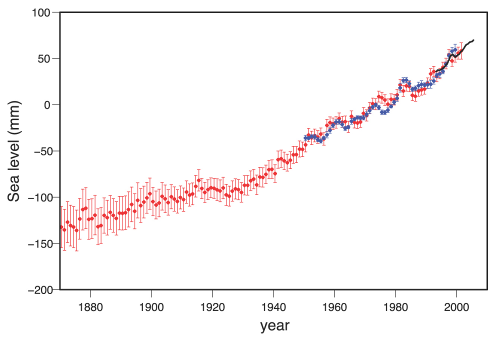

Figure 2. Annual averages of the global mean sea level (mm). The red curve shows reconstructed sea level fields since 1870; the blue curve shows coastal tide gauge measurements since 1950 and the black curve is based on satellite altimetry. The red and blue curves are deviations from their averages for 1961 to 1990, and the black curve is the deviation from the average of the red curve for the period 1993 to 2001. Error bars show 90% confidence intervals [IPCC AR4, Fig5.13].

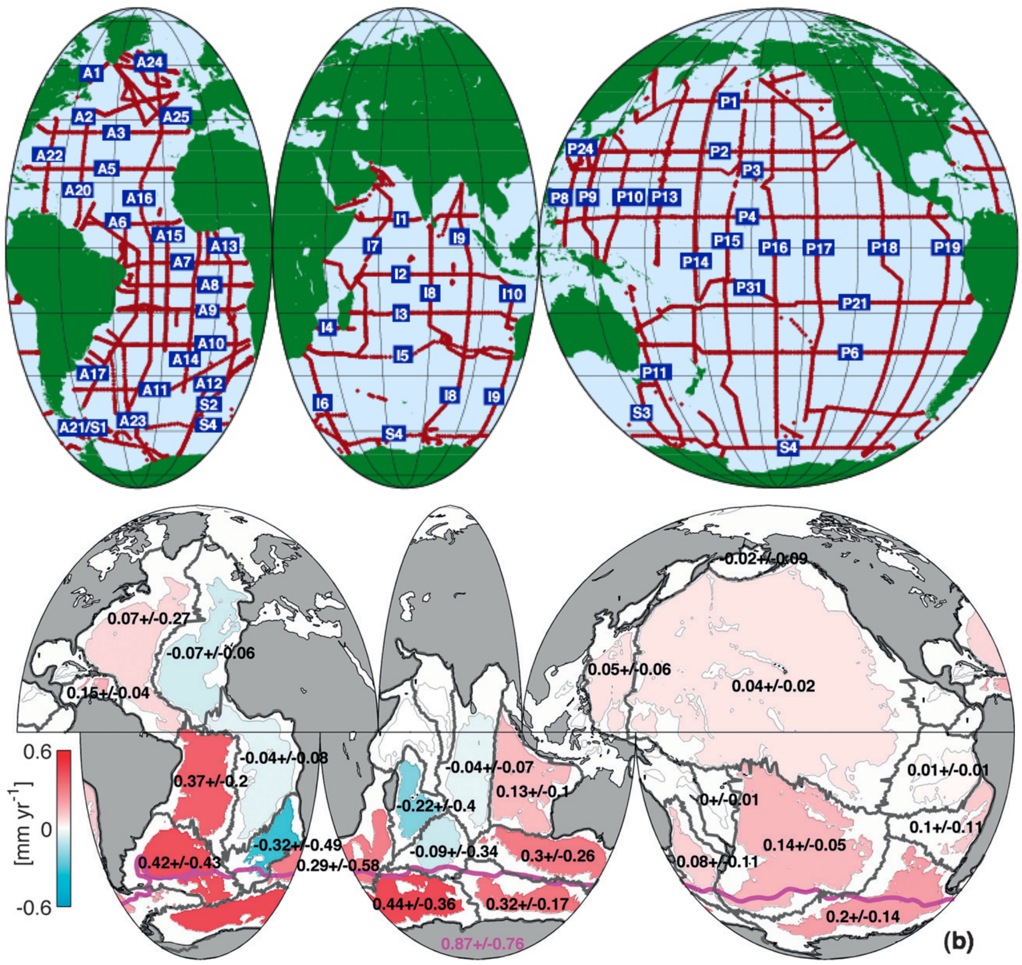

Figure 3. (top) Stations occupied during the World Ocean Circulation Experiment network of hydrographic sections [TAMU online: http://woceatlas.tamu.edu/Sites/html/atlas/SOA_WOCE.html]. Names such as "A1" denote WOCE hydrographic sections. (bottom) Sea level rise attributable to warming of Antarctic Bottom water. Basin means of sea level rise from the 1990s to the 2000s due to abyssal thermal expansion below 4000 m and deep thermal expansion in the Southern Ocean from 1000 to 4000 m south of the Sub-Antarctic Front. Basin boundaries (thick grey lines) and 4000 m isobath (thin black lines) are also shown. [8].

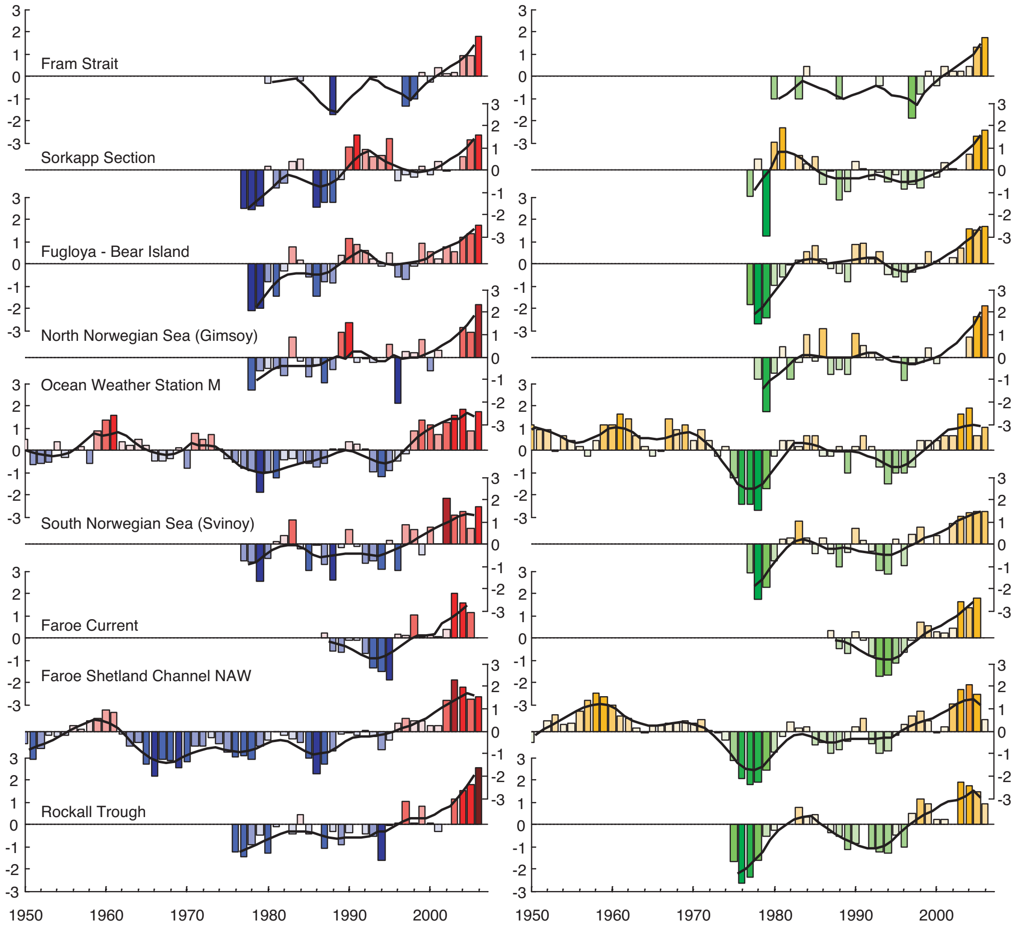

Figure 4. Time series of upper ocean temperature anomalies (left panel) and salinity anomalies (right panel) from sustained ocean observations along the pathways of Atlantic Inflow from the Rockall Trough (bottom) to the Fram Strait (top). Data are presented as normalised anomalies from the long-term mean (1988-2006 for Faroe Current and Fram Strait, 1978-2006 for all others) [10].

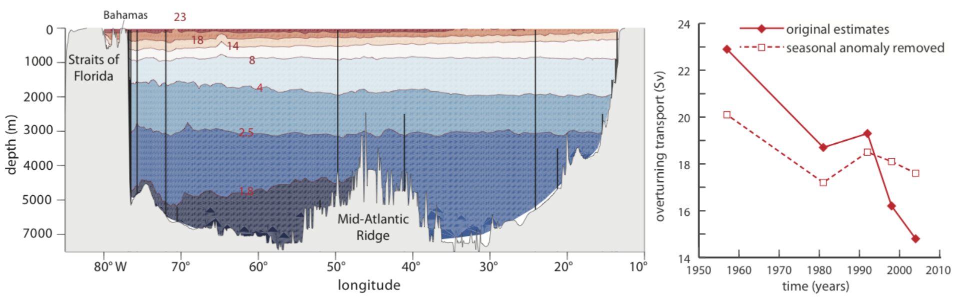

Figure 5. (left) Temperature section at 24°N in the Atlantic from the 2010 hydrographic cruise on the RRS Discovery. Black vertical lines indicate locations of moorings from the RAPID array. (right) Overturning transport estimated from five hydrographic sections in 1957, 1981, 1992, 1998 and 2004 (red, solid). Red dashed shows the transports from the hydrographic section corrected for the seasonal cycle of the MOC, as estimated from RAPID (2004–2007). Note the amplitude of the long term decrease from 1957 to 2004 is reduced once aliasing of the seasonal cycle is accounted for.

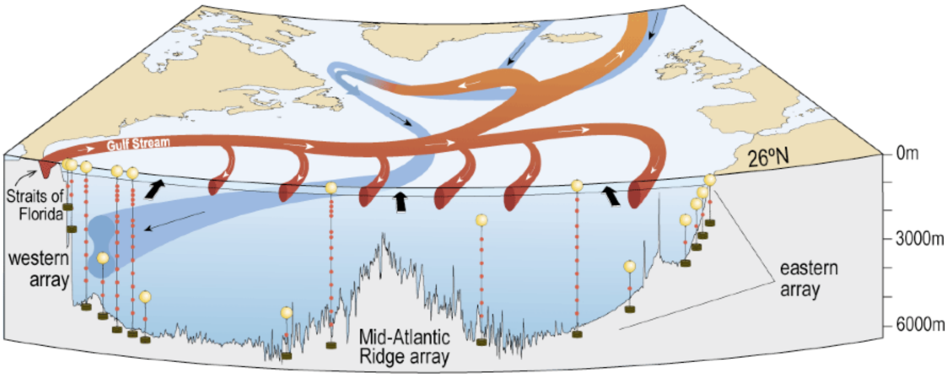

Figure 6. Diagram of the circulation in the North Atlantic. The surface circulation is shown in red, while the deep circulation in blue. The black arrows indicate the surface Ekman transport (northward in the mean).

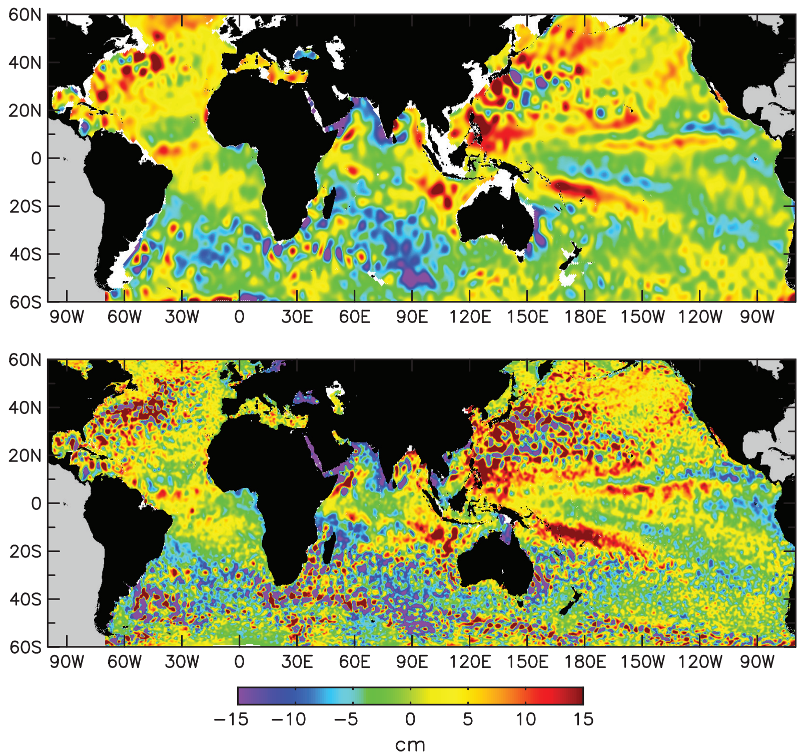

Figure 7. (top) An example of global maps of sea surface height on 28 August 1996 constructed from TOPEX/Poseidon (T/P) data only and from the merged T/P and ERS-1 data (bottom). Note the strong signal from energetic western boundary currents such as the Gulf Stream (60°W, 30°N), the Kuroshio (140°E, 30°N), and the Agulhas (30°E, 40°S). [18].

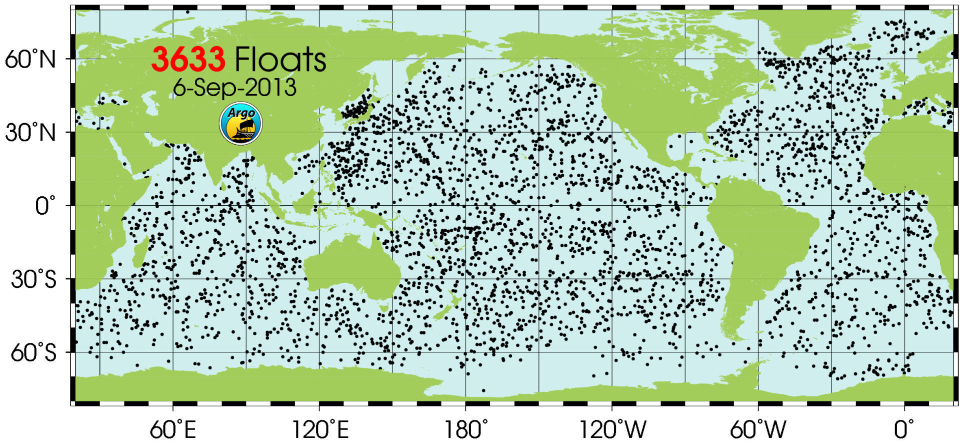

Figure 8. Argo float global network for 6 Sep 2013. Black dots indicate the most recent profile location for active floats.

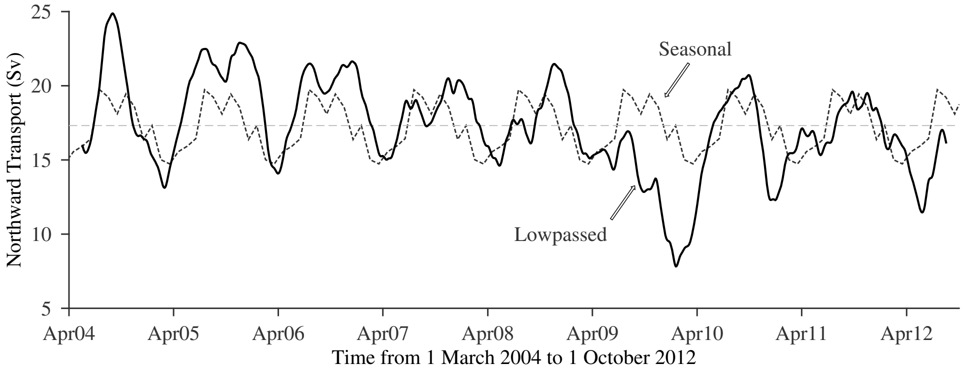

Figure 9. Time series of the overturning transport, with a 90-day Tukey lowpass filter applied (black solid) and the average annual cycle from the first four years (grey-dashed).

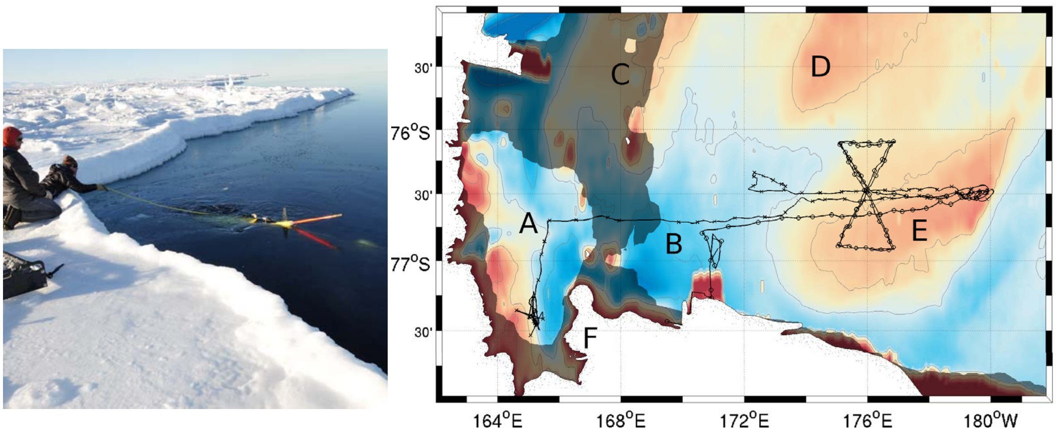

Figure 10. (left) Photograph showing the deployment of a Seaglider from the Ross Sea ice shelf. (right) Tracks of the glider during the 3 month deployment before being recovered from a vessel. [Figures from K. Heywood].

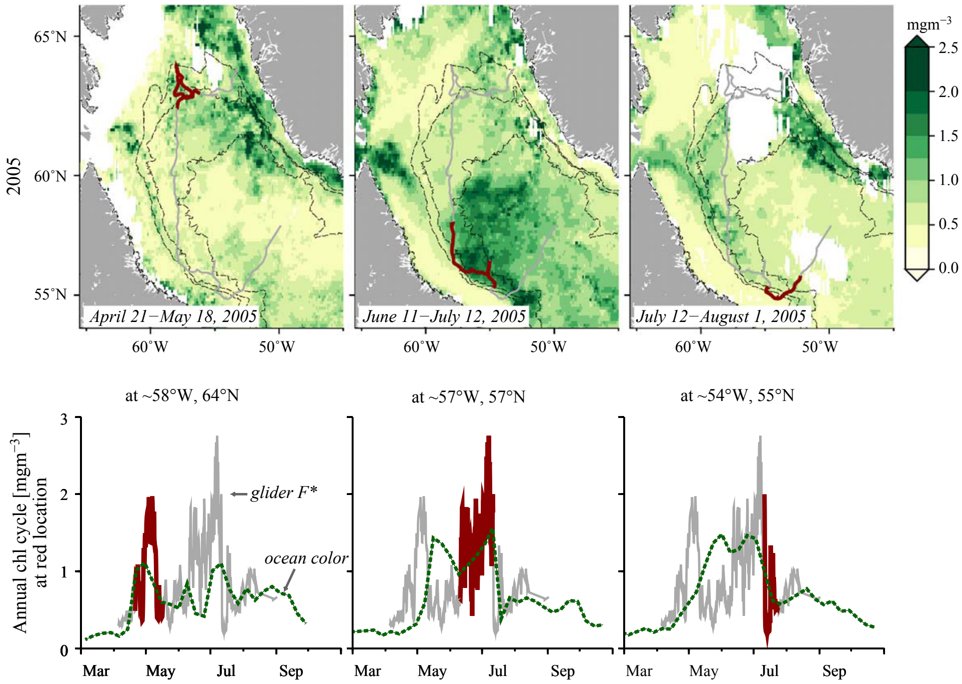

Figure 11. (top row) Surface chlorophyll in the Labrador Sea is shown in colour from SeaWiFS for the periods indicated, with the glider track overlaid in grey. The glider position during the periods indicated is in red. (bottom row) Glider chlorophyll measurements in the top 20 m are compared with the SeaWiFS annual cycle for the location indicated and averaged over 1998–2008 (green). Modified from [47].

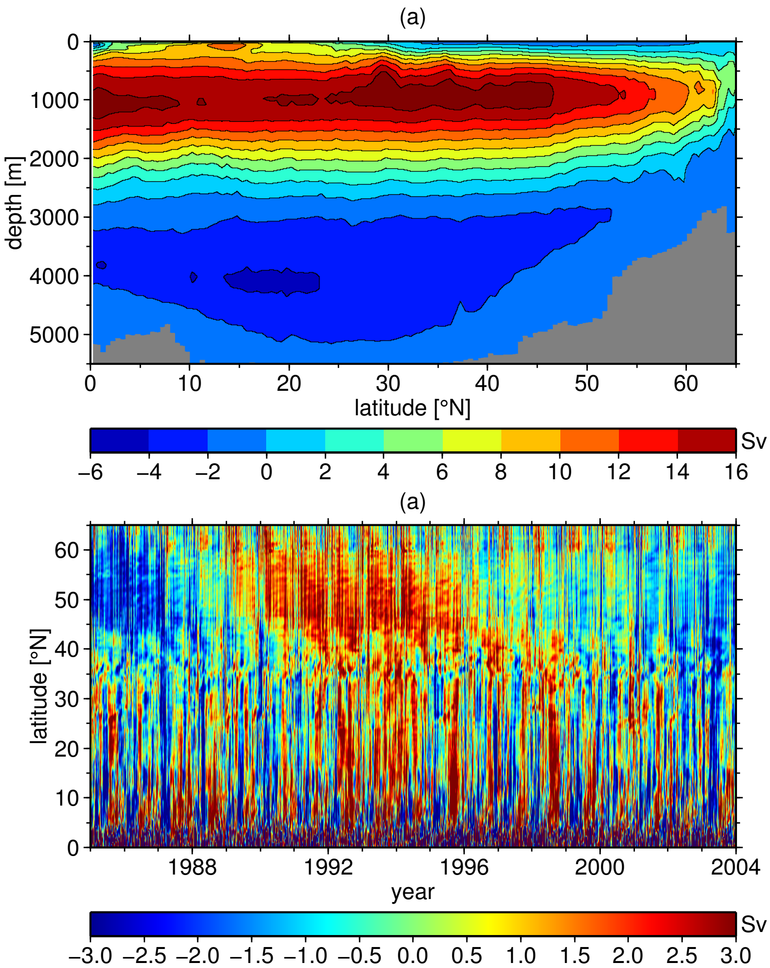

Figure 12. (a) The OCCAM time-averaged overturning stream function where colours indicate the strength of the transport in Sverdrups (1 Sverdrup= 10^6 km^{3}s^{-1}). (b) OCCAM northward transport anomaly between 100 m and 1000 m depth [53].

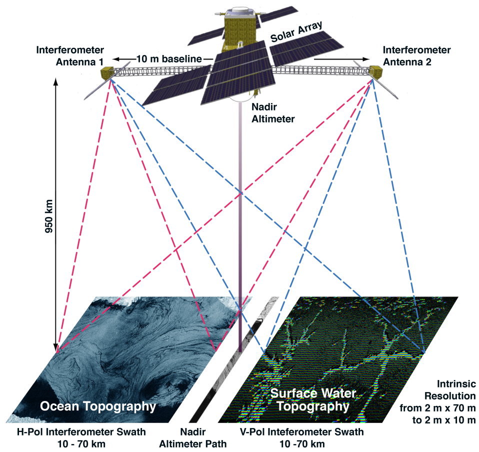

Figure 13. Configuration of a wide-swath altimetry mission based on the radar interferometry technique. The intrinsic resolution of synthetic aperture radar is on the order of a few meters, but noise in the measurement will require smoothing onto roughly 1 km×1 km grid, for accuracy of 1 cm [58].

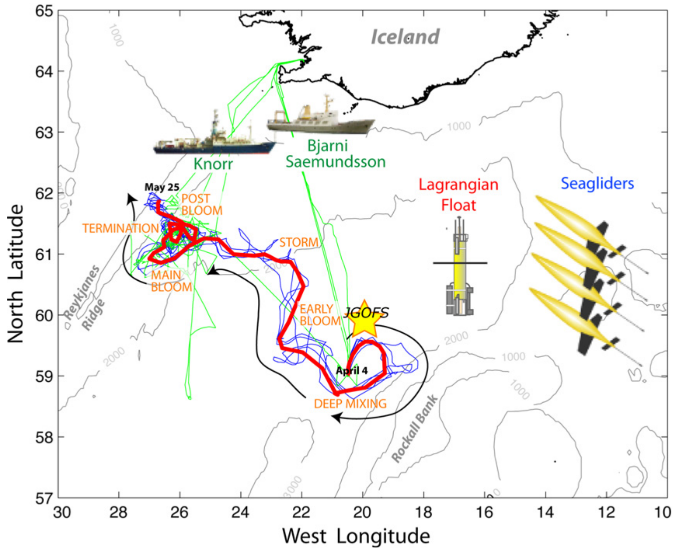

Figure 14. Map of study area for the North Atlantic Bloom Experiment. Track of Float 48 (red), Seagliders (blue) and cruises (green) are plotted as coloured lines. The direction of the float drift, beginning 4 Apr and ending 25 May, is illustrated using black arrows. The various bloom periods (Deep Mixing, Early Bloom, Storm, Main Bloom, Termination and Post-Bloom) are also included. The location of the JGOFS 1989 North Atlantic Bloom Experiment is plotted as a yellow star for reference. [63]

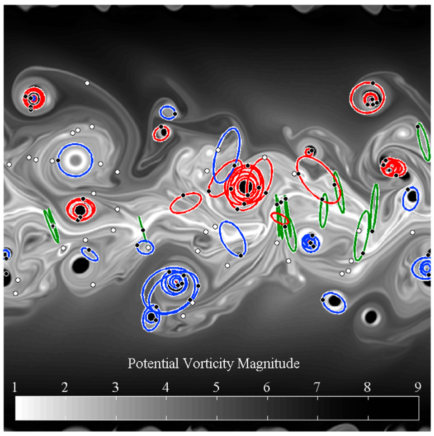

Figure 15. A snapshot of an unstable eastward equivalent barotropic jet on a mid-latitude beta plane. The shading is the absolute value of the quasigeostrophic potential vorticity. Estimated instantaneous ellipses due to Lagrangian oscillatory motions are overlaid. Highly eccentric ellipses with eccentricity $\epsilon > 0.95$ are shown in green, while positively-rotating and negatively-rotating ellipses with $\epsilon \leq 0.95$ are shown in red and blue, respectively. Dots mark the instantaneous locations of 100 Lagrangian particles initially deployed along the jet axis. Black dots indicate particles in which an oscillatory signal is detected at this moment, while white dots indicate the locations of other particles [65].

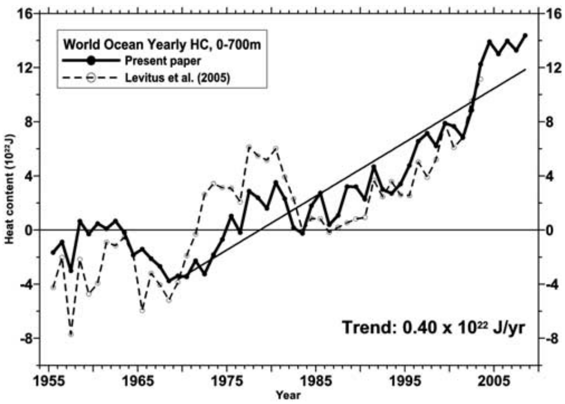

Figure 16. Time series of yearly ocean heat content (10^{22} J) for the 0–700 m layer (solid) and from a previous estimate prior to correcting for errors in XBT measurements [69]. Note the relatively warm period in the previous estimate (grey dashed) in the 1970s. The reference period is 1957–1990. [66]

References

1 Claire Postlethwaite, Anna Hickman, and Abigail McQuatters-Gollop. Sustained marine observations: Prospectus introduction. *Philosophical Transactions of The Royal Society*, 2014.

2 J. A. Church and N. J. White. Sea-level rise from the late 19th to the early 21st century. *Surv. Geophys.*, 32:585–602, 2011. doi: doi:10.1007/s10712Ð011-9119-1.

3 S. J. Holgate and P. L. Woodworth. Evidence for enhanced coastal sea level rise during the 1990s. *Geophysical Research Letters*, 31:L07305, 2004. doi: doi:10.1029/2004GL019626.

4 J. Gould, B. Sloyan, and M. Visbeck. In-situ ocean observations: A brief history, present status and future directions. In G. Siedler, S. Griffies, J. Gould, and J. Church, editors, *Ocean Circulation and Climate, 2nd Ed*, page pp. 904, San Diego, 2013. Academic Press.

5 Nicholas Owens. Sustained UK marine observations: Where have we been? Where are we now? Where are we going? *Philosophical Transactions of The Royal Society*, 2014.

6 F. Culkin and J. Smed. The history of standard seawater. *Oceanologica Acta*, 2(3):355–364, 1979.

7 Sheldon Bacon, Fred Culkin, Nigel Higgs, and Paul Ridout. Iapso standard seawater: Definition of the uncertainty in the calibration procedure, and stability of recent batches. *Journal of Atmospheric and Oceanic Technology*, 24:1785–1799, 2007. doi: 10.1175/JTECH2081.1.

8 Sarah G. Purkey and Gregory C. Johnson. Warming of global abyssal and deep southern ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets. *Journal of Climate*, 2010.

9 N. P. Holliday and S. A. Cunningham. The Extended Ellett Line: Discoveries from 65 years of marine observations west of the UK. *Oceanography*, 26(2), 2013.

10 N. Penny Holliday, S. L. Hughes, S. Bacon, A. Beszczynska-M oller, B. Hansen, A. LavŠn, H. Loeng, K. A. Mork, S. Osterhus, T. Sherwin, and W. Walczowski. Reversal of the 1960s to 1990s freshening trend in the northeast North Atlantic and Nordic Seas. *Geophysical Research Letters*, 35:L03614, 2008. doi: 10.1029/2007GL032675.

11 Harry L. Bryden and S. Imawaki. Ocean heat transport. In G. Siedler, J. Church, and J. Gould, editors, *Ocean circulation and climate*, pages 455–474, New York, NY, 2001. Academic Press.

12 Harry L. Bryden, Hannah R. Longworth, and Stuart A. Cunningham. Slowing of the Atlantic meridional overturning circulation at 25°N. *Nature*, 438:655–657, 2005.

13 William E. Johns, M. O. Baringer, L. M. Beal, S. A. Cunningham, T. Kanzow, H. L. Bryden, J. J.-M. Hirschi, J. Marotzke, C. S. Meinen, B. Shaw, and R. Curry. Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5°N. *Journal of Climate*, 24:2429–2449, May 2011.

14 T. Tsubouchi, S. Bacon, A. C. Naveira Garabato, Y. Aksenov, S. W. Laxon, E. Fahrbach, A. Beszczynska-Möller, E. Hansen, C. M. Lee, and R. B. Ingvaldsen. The Arctic Ocean in summer: A quasi-synoptic inverse estimate of boundary fluxes and water mass transformation. *Journal of Geophysical Research*, 117:C01024, 2012. doi: 10.1029/2011JC007174.

15 K. J. Heywood, R. Muench, and G. Williams. An overview of the synoptic Antarctic shelf-slope interactions (SASSI) project for the International Polar Year. *Ocean Science*, 8:1117–1122, 2012. doi: 10.5194/os-8-1117-2012.

16 Michael P. Meredith, Philip L. Woodworth, Teresa K. Chereskin, David P. Marshall, Lesley C. Allison, Grant R. Bigg, Kathy Donohue, Karen J. Heywood, Chris W. Hughes, Angela Hibbert, Andrew McC. Hogg, Helen L. Johnson, LoŢc Jullion, Brian A. King, Harry Leach, Yueng-Djern Lenn, Miguel A. Morales Maqueda, David R. Munday, Alberto C. Naveira Garabato, Christine Provost, Jean-Baptiste Sallée, and Janet Sprintall. Sustained monitoring of the Southern Ocean at Drake Passage: Past achievements and future priorities. *Reviews of Geophysics*, 49:RG4005, 2011. doi: 10.1029/2010RG000348.

17 Povl Abrahamsen. Sustained UK marine observations of the polar regions? *Philosophical Transactions of The Royal Society*, 2014.

18 Dudley B. Chelton, M. G. Schlax, and R. M. Samelson. Global observations of nonlinear mesoscale eddies. *Progress in Oceanography*, 91:167–216, 2011.

19 Carl Wunsch and Raffaele Ferrari. Vertical mixing, energy and the general circulation of the oceans. *Annual Reviews in Fluid Mechanics*, 36:281–314, 2004.

20 R. B. Scott et al. Satellite altimetry and key observations: What we've learned, and what's possible with new technologies. In J. Hall, D. E. Harrison, and D. Stammer, editors, *In Proc. of OceanObs'09: sustained ocean observations and information for society, Venice, Italy, 21–25 September 2009, vol. 2*. ESA Publication WPP-306, 2010. doi: doi:10.5270/OceanObs09.cwp.23.
21 P. Y. Le Traon. From satellite altimetry to Argo and operational oceanography: three revolutions in oceanography. *Ocean Science Discussions*, 10:1127–1167, 2013. doi: 10.5194/osd-10-1127-2013.
22 Nikolai A. Maximenko, Pearn P. Niiler, Marie-Helena Rio, Oleg V. Melnichenko, Luca Centurioni, Don Chambers, Victor Zlotnicki, and Boris Galperin. Mean dynamic topography of the ocean derived from satellite and drifting buoy data using three different techniques. *Journal of Atmospheric and Oceanic Technology*, 26:1910–1919, 2009.
23 Mark Tamisiea. Sustained marine observations: Sea level. *Philosophical Transactions of The Royal Society*, 2014.
24 D. Roemmich, G. C. Johnson, S. L. Garzoli, C. Schmid, and M. Ignaszewski. The Argo program: observing the global ocean with profiling floats. *Oceanography*, 22:34–43, 2009. doi: doi:10.5670/oceanog.2009.36.
25 D. Roemmich and J. Gilson. The 2004–2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program. *Progress in Oceanography*, 82:81–100, 2009. doi: 10.1016/j.pocean.2009.03.004.
26 Sarah L. Taws, Robert Marsh, Neil C. Wells, and Joël J.-M. Hirschi. Re-emerging ocean temperature anomalies in late-2010 associated with a repeat negative NAO. *Geophysical Research Letters*, 38:L20601, 2011. doi: 10.1029/2011GL048978.
27 Bruce Ingleby and Matt Huddleston. Quality control of ocean temperature and salinity profiles—Historical and real-time data. *Journal of Marine Systems*, 65:158–175, 2007. doi: 10.1016/j.jmarsys.2005.11.019.
28 C. Wunsch, P. Heimbach, R. M. Ponte, and I. Fukumori. The global general circulation of the ocean estimated by the ecco consortium. *Oceanography*, 22(2), 2009.
29 N. J. Dunstone. Climate modelling and prediction. *Philosophical Transactions of The Royal Society*, 2014.
30 Helen L. Johnson and David P. Marshall. Localization of abrupt change in the north atlantic thermohaline circulation. *Geophysical Research Letters*, 29(6), 2002. doi: 10.1029/2001GL014140.
31 Helen L. Johnson and D. P. Marshall. A theory for the surface Atlantic response to thermohaline variability. *Journal of Physical Oceanography*, 32:1121–1132, 2002.
32 C. R. Downes. History of the British ocean weather ships. *The Marine Observer*, 47:179–186, 1977.
33 Nick Bates. Sustained marine observations: Bermuda Atlantic Time Series. *Philosophical Transactions of The Royal Society*, 2014.
34 M. J. McPhaden. El Niño and ocean observations: a personal history. In G. Siedler, J. Church, and J. Gould, editors, *Physical oceanography, developments since 1950*, pages 99–122, New York, NY, 2006. Academic Press.
35 Darren Rayner, J. J.-M. Hirschi, Torsten Kanzow, W. E. Johns, Paul G. Wright, Eleanor Frajka-Williams, Harry L. Bryden, Christopher S. Meinen, Molly O. Baringer, Jochem Marotzke, Lisa M. Beal, and Stuart A. Cunningham. Monitoring the Atlantic meridional overturning circulation. *Deep Sea Research II*, 58:1744–1753, 2011.
36 Stuart A. Cunningham, Torsten Kanzow, Darren Rayner, Molly O. Baringer, William E. Johns, Jochem Marotzke, Hannah R. Longworth, Elizabeth M. Grant, Joel J.-M. Hirschi, Lisa M. Beal, Christopher S. Meinen, and Harry L. Bryden. Temporal variability of the Atlantic meridional overturning circulation at 26.5°N. *Science*, 317:935–938, 2007.
37 T. Kanzow, S. A. Cunningham, W. E. Johns, J. J-M. Hirschi, J. Marotzke, M. O. Baringer, C. S. Meinen, M. P. Chidichimo, C. Atkinson, L. M. Beal, H. L. Bryden, and J. Collins. Seasonal variability of the Atlantic meridional overturning circulation at 26.5°N. *Journal of Climate*, 23:5678–5698, 2010. doi: 10.1175/2010JCLI3389.1.
38 Gerard McCarthy, Eleanor Frajka-Williams, William E. Johns, M. O. Baringer, C. S. Meinen, H. L. Bryden, D. Rayner, A. Duchez, C. D. Roberts, and S. A. Cunningham.

Observed interannual variability of the Atlantic meridional overturning circulation at 26.5°N. *Geophysical Research Letters*, page L19609, 2012. doi: 10.1029/2012GL052933.

39 D. A. Smeed, G. McCarthy, S. A. Cunningham, E. Frajka-Williams, et al. Observed decline of the Atlantic meridional overturning circulation 2004 to 2012. *Ocean Science*, 10:29–38, 2014. doi: 10.5194/os-10-29-2014.

40 Stuart A. Cunningham, Chris Roberts, Eleanor Frajka-Williams, W. E. Johns, W. Hobbs, Matt D. Palmer, D. Rayner, D. A. Smeed, and G. McCarthy. Atlantic meridional overturning circulation slowdown cooled the subtropical ocean. *Geophysical Research Letters*, 2014. doi: 10.1002/2013GL058464.

41 C. D. Roberts, J. Waters, K. A. Peterson, M. Palmer, G. D. McCarthy, E. Frajka-Williams, K. Haines, D. J. Lea, M. J. Martin, D. Storkey, E. W. Blockley, and H. Zuo. Atmosphere drives observed interannual variability of the atlantic meridional overturning circulation at 26.5°n. *Geophysical Research Letters*, 40:1–7, 2013. doi: 10.1002/grl.50930.

42 A. Jenkins, P. Dutrieux, S. S. Jacobs, S. D. McPhail, J. R. Perrett, A. T. Webb, and D. White. Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat. *Nature Geoscience*, 3:468–472, 2010. doi: doi:10.1038/ngeo890.

43 Henry Stommel. The Slocum mission. *Oceanus*, 32:93–96, 1989.

44 K. J. Heywood et al. Seaglider deployments in the Antarctic: Ross, Weddell and Amundsen Seas. *UK Glider Workshop, 18 Apr 2013*, 2013.

45 Eleanor Frajka-Williams, Peter B. Rhines, and Charles C. Eriksen. Horizontal stratification during deep convection in the Labrader Sea. *Journal of Physical Oceanography*, in press.

46 Daniel L. Rudnick and Sylvia T. Cole. On sampling the ocean using underwater gliders. *Journal of Geophysical Research*, 116:C08010, 2011. doi: 10.1029/2010JC006849.

47 Eleanor Frajka-Williams, Peter Rhines, and Charles Eriksen. Physical controls and mesoscale variability in the Labrador Sea spring phytoplankton bloom observed by Seaglider. *Deep Sea Research I*, 56:2144–2161, 2009.

48 Mario Brito, David Smeed, and Gwyn Griffiths. Undersea glider reliability and implications for survey design *submitted*. *Journal of Atmospheric and Oceanic Technology*, 2013.

49 Dean Roemmich and Co-Authors. Integrating the ocean observing system: Mobile platforms. In J. Hall, D. E. Harrison, and D. Stammer, editors, *Proc. of OceanObs'09: sustained ocean observations and information for society, Venice, Italy, 21–25 September 2009, vol. 2*. ESA Publication WPP-306, 2010.

50 Matthew D. Palmer, Douglas J. McNeall, and Nick J. Dunstone. Importance of the deep ocean for estimating decadal changes in Earth's radiation balance. *Geophysical Research Letters*, 38: L13707, 2011. doi: 10.1029/2011GL047835.

51 Annie P. S. Wong and Stephen C. Riser. Profiling float observations of the upper ocean under sea ice off the Wilkes land coast of Antarctica. *Journal of Physical Oceanography*, 41:1102–1115, 2011.

52 Shane Elipot, Chris Hughes, Sofia Olhede, and John Toole. Coherence of western boundary pressure at the rapid wave array: boundary wave adjustments or deep western boundary current advection? *Journal of Physical Oceanography*, 43:744–765, 2013.

53 Rory J. Bingham, Chris W. Hughes, Vassil Roussenov, and Richard G. Williams. Meridional coherence of the North Atlantic meridional overturning circulation. *Geophysical Research Letters*, 34:L23606, 2007. doi: 10.1029/2007GL031731.

54 S. Cunningham and Co-Authors. The present and future system for measuring the Atlantic meridional overturning circulation and heat transport. In J. Hall, D. E. Harrison, and D. Stammer, editors, *Proceedings of OceanObsÕ09: Sustained Ocean Observations and Information for Society (Vol. 2)*. ESA Publication WPP-306, 2010. doi: 10.5270/OceanObs09.pp.32.

55 Sheldon Bacon and Peter M. Saunders. The deep western boundary current at Cape Farewell: Results from a moored current meter array. *Journal of Physical Oceanography*, 40:815–829, 2010. doi: 10.1175/2009JPO4091.1.

56 N. P. Holliday, S. Bacon, J. Allen, and E. L. McDonagh. Circulation and transport in the western boundary currents at Cape Farewell, Greenland. *Journal of Physical Oceanography*, 39:1854–1870, 2009.

57 Christopher S. Meinen, Sabrina Speich, Renellys C. Perez, Shenfu Dong, Alberto R. Piola, Silvia L. Garzoli, Molly O. Baringer, Sergey Gladyshev, and Edmo J. D. Campos. Temporal variability of the meridional overturning circulation at 34.5°s: Results from two pilot boundary arrays in the South Atlantic. *Journal of Geophysical Research*, 118:6461–6478, 2013. doi: 10.1002/2013JC009228.

58 L.-L. Fu, D. B. Chelton, P.-Y. Le Traon, and R. Morrow. Eddy dynamics from satellite altimetry. *Oceanography*, 23:14–25, 2010. doi: 10.5670/oceanog.2010.02.

59 Nicholas Beaird, Ilker Fer, Peter Rhines, and Charles Eriksen. Dissipation of turbulent kinetic energy inferred from Seagliders: An application to the eastern Nordic Seas overflows. *Journal of Physical Oceanography*, 42:2268–2282, 2012. doi: 10.1175/JPO-D-12-094.1.

60 Patrick F. Cummins, G. Holloway, and E. Gargett. Sensitivity of GFDL ocean general circulation model to a parameterization of vertical diffusion. *Journal of Physical Oceanography*, 20:817–830, 1990. doi: 10.1175/1520-0485(1990)020<0817:SOTGOG>2.0.CO;2.

61 G. Danabasoglu, S. Yaeger, and et al. North Atlantic simulations in Coordinated Ocean-ice Reference Experiments, phase ii (CORE-II): Part I: Mean states. *Ocean Modelling*, 73:76–107, 2014.

62 Eleanor Frajka-Williams, Charles C. Eriksen, Peter B. Rhines, and Ramsey R. Harcourt. Determining vertical velocities from Seaglider. *Journal of Atmospheric and Oceanic Technology*, 28:1641–1656, 2011.

63 Matthew B. Alkire, Eric D'Asaro, Craig Lee, Mary Jane Perry, Amanda Gray, Ivona Cetinić, Nathan Briggs, Eric Rehm, Emily Kallin, Jan Kaiser, and Alba González-Posada. Estimates of net community production and export using high-resolution, Lagrangian measurements of O_2, NO_3, and POC through the evolution of a spring diatom bloom in the North Atlantic. *Deep Sea Research I*, 64:157–174, 2012. doi: 10.1016/j.dsr.2012.01.012.

64 Kathleen Dohan and Nikolai Maximenko. Monitoring ocean currents with satellite sensors. *Oceanography*, 23:94–103, 2010. doi: 10.5670/oceanog.2010.08#sthash.0hxUZZCC.dpuf.

65 Jonathan M. Lilly, R. K. Scott, and S. C. Olhede. Extracting waves and vortices from Lagrangian trajectories. *Geophysical Research Letters*, 38:L23605, 2011. doi: 10.1029/2011GL049727.

66 S. Levitus, J. I. Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, and A. V. Mishonov. Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophysical Research Letters*, 36:L07608, 2009. doi: 10.1029/2008GL037155.

67 D. James Baker, Raymond W. Schmitt, and Carl Wunsch. Endowments and new institutions for long-term observations. *Oceanography*, 20(4):10–14, 2007.

68 S. A. Henson. Slow science: the value of long ocean biogeochemistry records. *Philosophical Transactions of The Royal Society*, 2014.

69 S. Levitus, J. I. Antonov, and T. P. Boyer. Warming of the world ocean, 1955–2003. *Geophysical Research Letters*, 32:L02604, 2005. doi: 10.1029/2004GL021592.