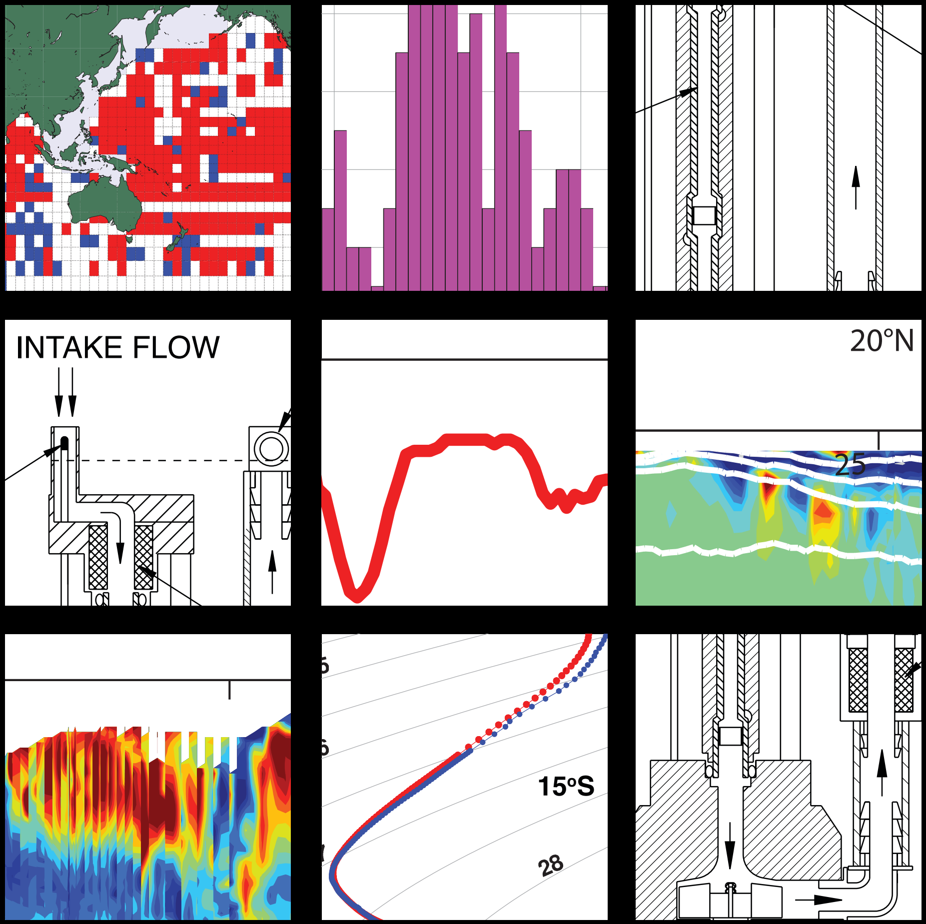
BY STEPHEN C. RISER, LI REN, AND ANNIE WONG

SALINITY IN ARGO



A MODERN VIEW OF A CHANGING OCEAN

MOTIVATION AND HISTORY

The salinity distribution in the ocean is just one manifestation of the global hydrological cycle, which also involves ice and snow, terrestrial water storage, the atmosphere, and the biosphere. Water exchange among these reservoirs is determined by complicated mechanical and thermodynamical constraints that form the basis of climate dynamics. Yet the freshwater signal in the ocean, and its close relative, ocean salinity, may well be the most difficult of these global-scale reservoirs to observe. Salinity in the ocean is determined by evaporation, precipitation, runoff, and ice formation and melting—and ocean circulation—effects that can operate at local to global spatial scales.

Through its role in determining seawater density, salinity (along with its counterpart, temperature) has a direct effect on ocean circulation at all scales. At global scales, satellites can measure sea-surface temperature rapidly, while at smaller scales, a variety of techniques are used. In a few years, the Aquarius satellite mission will produce analogous global measurements of sea-surface salinity (see Lagerloef et al., this issue). Subsurface temperature and salinity have long been measured from ships, but generally it has not been possible to infer these parameters at global spatial scales and weekly temporal scales, a necessity for examining the ocean's role in climate and the storage of heat and freshwater.

To understand the history of inferring the large-scale properties of the subsurface ocean, consider the distribution of subsurface temperature and salinity data over the past 50 years. Ships began making measurements of subsurface temperature and salinity more than a century ago, yet by the late 1970s there were many parts of the world ocean where deep data had never been collected. This dearth of data can be seen in Worthington's (1981) map of the locations of quality temperature and salinity observations available through the late 1970s (Figure 1a). Although many good observations of upper ocean temperature and salinity existed at that time, Worthington's study showed that in much of the world, the deep sea was completely unsampled. Worthington defined unsampled as a situation where no good-quality temperature and salinity observations existed in the deepest part of the ocean in any 5-degree square (see red squares in Figure 1a). Owing to the limited capability of making quality measurements of temperature and salinity in the deep sea at that time, it is probably fair to assume that many of these red squares contained no quality data even to depths of 2000 m. As is evident in Worthington's figure, only the North Atlantic was relatively well sampled through the 1970s; the temperature and salinity properties of the deep North Pacific and the Southern Hemisphere oceans had, to a great extent, never been sampled.

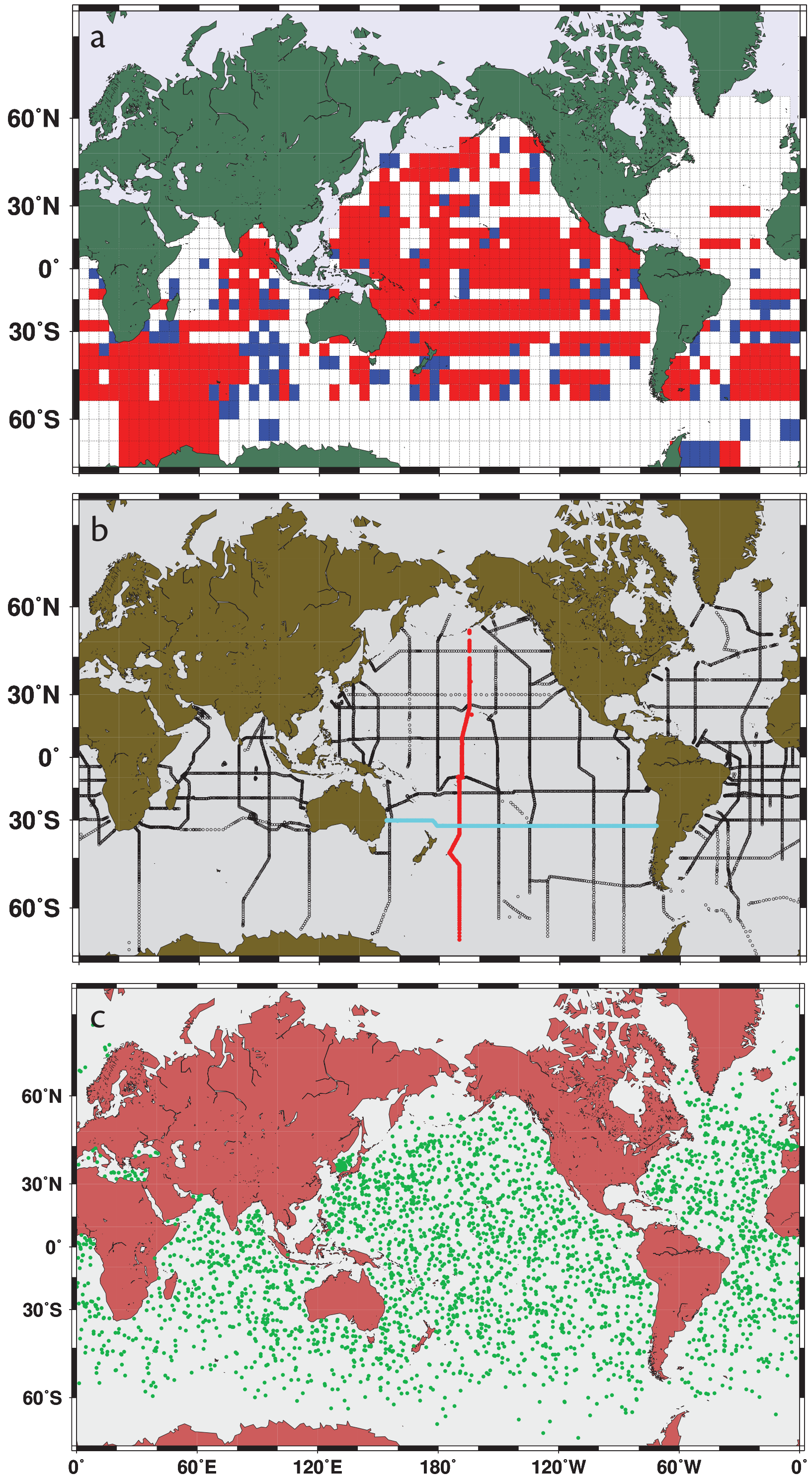


Figure 1. (a) The distribution of high-quality, deep-sea temperature and salinity stations by 5° squares in the world ocean as of 1977, redrawn from Worthington (1981). White squares denote areas where there was at least one high-quality station with data collected from the surface to near the bottom. Blue squares indicate at least one high-quality station with data to the bottom, but where the bottom was not in a deep part of the square. Red squares show areas where there were no deep data in existence as of 1977. (b) Black, red, and blue lines show CTD sections collected as part of the World Ocean Circulation Experiment (WOCE), from 1985-1997. The red line shows WOCE P15 and the blue line indicates the track of the R/V *Mirai* on a repeat of a WOCE line in 2003. (c) Locations of nearly 3000 Argo floats in the world ocean as of mid 2007.

To remedy this situation, the World Ocean Circulation Experiment (WOCE) was initiated in the mid 1980s with the goal of completing a survey of the world ocean from top to bottom, essentially filling the colored squares in Figure 1a with good temperature and salinity data to the greatest extent possible. As illustrated in Figure 1b, WOCE data were collected along a series of long sections throughout the world ocean, eliminating many of the unsampled portions of Worthington's map. A great deal of effort went into ensuring that these data were of the highest possible quality, so that this one-time WOCE survey would be useful as a benchmark for future observers; this care resulted in accuracies in temperature (0.001°C) and salinity (0.001, Practical Salinity Scale of 1978 [PSS-78], used throughout this article) that cannot generally be surpassed with shipboard systems today. It took more than 12 years (from 1985 to 1997) to collect observations along all of these lines. So, while the WOCE data were global and of extremely high quality, they were far from synoptic.

As WOCE was ending, interest in the ocean's role in climate variability was strongly increasing. In order to monitor the subsurface ocean and to examine its role in decade-to-century-scale climate variability, it was clear that measurements of the subsurface ocean were

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required in real time and on a global scale. Because data collection from ships alone could not provide the requisite observations, a multinational group of oceanographers formulated a different plan—to deploy a large number of profiling floats over the globe at approximately 300-km spatial resolution that would each collect conductivity-temperature-depth (CTD) data to 2000 m and report the measurements in real time to global data centers where the observations would be publicly available. The ongoing Argo project, which began in 2000, was the result of this plan, although some technology development was necessary before float deployments in large numbers could begin. Profiling floats had been used during the WOCE years, but the emphasis had been on subsurface velocity data (Davis, 1998). To be a useful and cost-effective technique for ocean climate monitoring, Argo floats had to collect quality measurements of temperature and salinity to depths of 2000 m at 10-day intervals while unattended over periods of four to five years. These requirements seemed difficult, especially for salinity. During WOCE, the accurate salinity measurements obtained required the painstaking collection of many concomitant water samples on each CTD cast, analysis of these samples using standard water and a shipboard salinometer, and the subsequent adjustment of the CTD-measured values for consistency with the water samples on a cast-by-cast basis. For profiling floats, where the instrument operates autonomously after deployment and is generally never again seen, such a calibration exercise is impossible. Thus, for Argo, innovative strategies for making salinity measurements useful in climate research were required.

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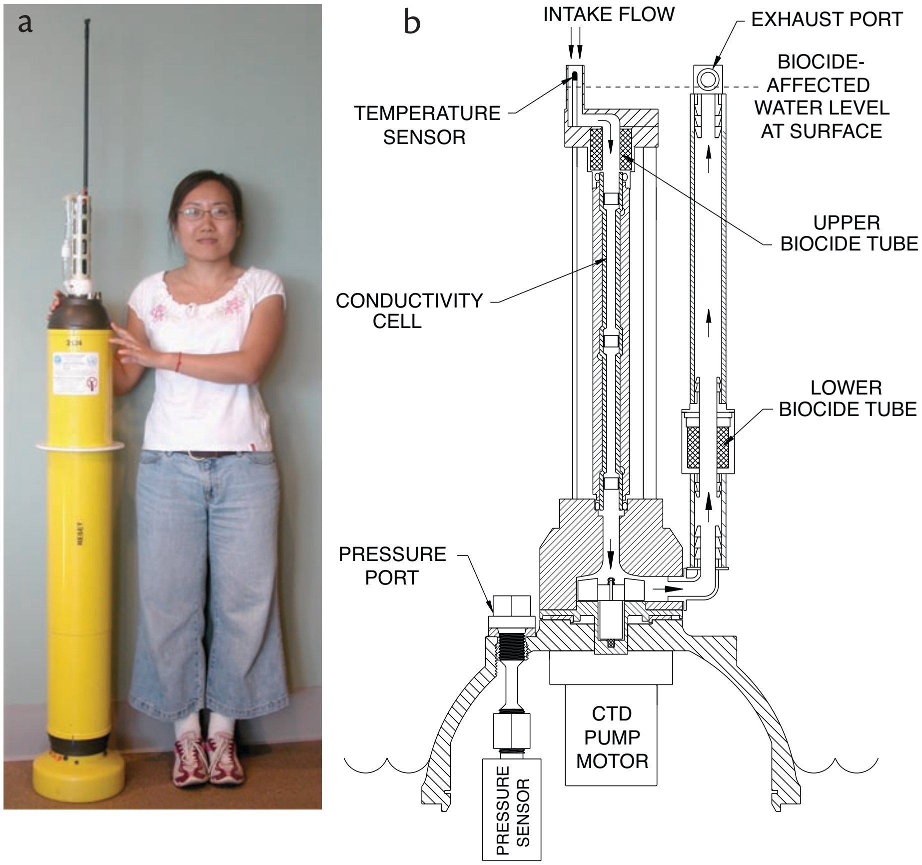
By October of 2007 (Figure 1c) the number of active Argo floats had reached the 3000 target. Coverage was essentially global except in the Southern Ocean. The evolution of our ability to observe the ocean, from the 1970s, through WOCE, and into the Argo program, is strikingly evident by comparing the three panels in Figure 1. Much of this progress was made possible through development of innovative sensor technology and real-time capabilities to transmit large amounts of data, which did not exist in a mature form until WOCE was nearly finished. Central to all of these advances has been the willingness of governmental agencies in many countries to provide the funds necessary to carry out the requisite technological developments and purchase and deploy the floats used in Argo.

FLOAT TECHNOLOGY AND SALINITY

The density of a seawater parcel is defined by its mass divided by its volume, and it is this relationship that profiling floats employ to ascend and descend between their parking depth and the sea surface. By inflating an external bladder, the floats can alter their volumes while maintaining constant mass, thus changing their density and allowing them to cycle vertically. Operation of these floats has by now become well known, as described by Roemmich et al. (2004), Davis et al. (2001), and Davis and Zenk (2001). It is the accurate and stable measurement of temperature and salinity, collected during the ascent phase, that allows successful use of these floats in an application like Argo.

A typical profiling float (Figure 2a) is about 2 m in length and has a mass of about 25 kg in air. The relatively small size permits deployment from a wide variety of platforms, including research vessels, container ships, fishing boats, and aircraft. The CTD unit is located on the upper end cap of the float (see detail in Figure 2b). Currently, most floats measure temperature, conductivity (from which salinity can be computed), and pressure at about 70 points during their ascent from 2000 m to the sea surface; Figure 2c shows a typical Argo profile.

In Argo applications, the CTD pump is turned off as the float ascends through a depth of 5 m, thus effectively trapping 5-m water in the cell as the float continues to ascend and break the sea surface. As Figure 2b shows, at the surface (while the float is transmitting its data to a satellite overhead) the CTD unit stands above the water level. Turning off the



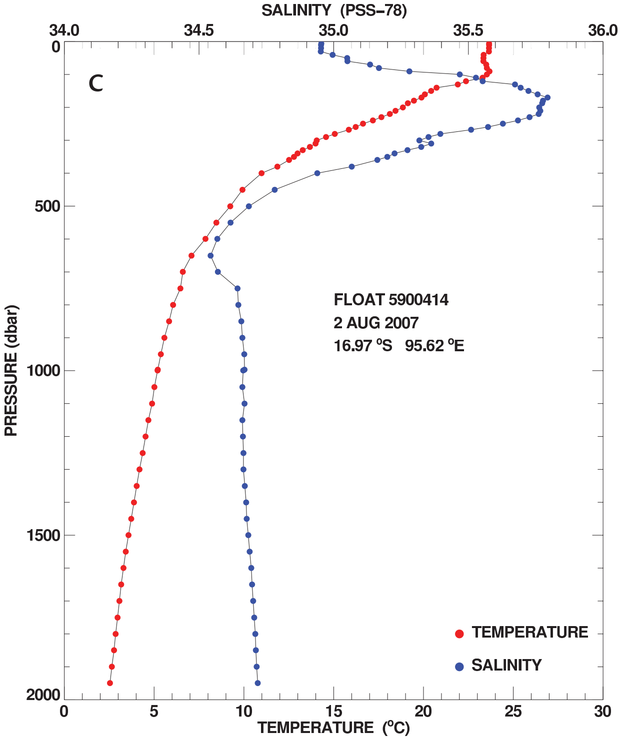


Figure 2. (a) A profiling float used in Argo, shown with co-author Li Ren. (b) A schematic drawing of the SeaBird CTD unit used on over 90% of the profiling floats deployed in Argo. The CTD unit operates by pumping seawater through a fluid circuit as the float ascends through the water column. Seawater enters the unit at the intake, and its temperature and electrical conductivity are measured as the fluid passes these sensors. Fluid in the cell exits through an exhaust port aligned perpendicular to the intake, so as not to contaminate the water entering the cell. The pressure of the sample is measured a few centimeters away from the fluid circuit via a sensor mounted inside the end cap. (c) Typical temperature and salinity data from a single Argo profile.

CTD pump at a depth of 5 m ensures that no near-surface flotsam and jetsam are pumped into the CTD unit. This has the positive effect of keeping the CTD cell clean over long periods of time (several years), but, as a consequence, we are not able to measure true sea surface temperature and salinity with these floats.

Inferring salinity via the direct measurement of seawater conductivity can, in principle, yield highly accurate salinity estimates over the several year time period required by Argo. Lueck (1990) analyzed the properties of the conductivity cells (both for conductivity and temperature) in CTD units similar to those used on Argo floats; his results indicate that even a very small amount of contamination in the conductivity cell can lead to significant errors in estimating salinity. Thus, the estimation of salinity by this method requires a precise knowledge of the geometry of the conductivity cell, especially its inside diameter. Lueck's model equations show that a coating on the inside of the cell even 1 micron in thickness (a biological film or oil, for example) can result in salinity errors of 0.01 or more. Therefore, precautions must be taken to ensure that contaminants do not enter and remain in the conductivity cell. Turning off the CTD pump at a depth of 5 m is one way to help keep the cell clean, as noted above. Because Argo floats typically spend about 95% of their lifetimes at depths below the thermocline (they are only in the euphotic zone and at the sea surface for a few hours during each 10-day cycle), there is only a small probability that organisms will attach themselves as they are pumped through the cell and subsequently grow there. To reduce even this small probability even further, a strong biocide is injected at both the intake port and just past the end of the conductivity cell. This kills any biological material that might get lodged or trapped in the cell, effectively prohibiting any contamination and subsequent degradation of the salinity estimates.

THE QUALITY OF ARGO SALINITY DATA

As Argo was being conceived, the experiment planners proposed a set of goals for float-array measurement quality. They chose long-term (4–5 year) accuracies of 0.005°C for temperature, 5 decibars for pressure, and 0.01 for salinity as the targets for the floats because they considered data of this quality necessary to be of maximal value in climate studies at present and in the coming decades. Although it seemed straightforward to measure temperature and pressure with this quality over extended periods (moored measurements of these quantities had already essentially achieved these accuracies), attaining the targeted accuracy for salinity over extended deployment periods was thought by many in the oceanographic community to be unlikely or impossible. Yet, a multiyear study from the very first float equipped with a SeaBird CTD system showed remarkable stability in salinity over times of three years (a salinity drift of only 0.006 after 1096 days in the ocean), based on recovery of the float at sea and subsequent laboratory recalibration. Soon, there were other occasional float recoveries by Argo scientists, and, where possible, these floats were immediately returned to the factory for recalibration (Oka, 2005). Invariably, recalibration results were similar to those of the first float: after an extended period in the water, the drift of the salinity measurement (as well as pressure and temperature) was close to the standards formulated at the beginning of Argo (shown in Table 1). The excellent quality of the salinity data was generally attributed to three factors, as previously noted: the CTD pump is turned off at a depth of 5 m, keeping surface film contamination out of the conductivity cell; the floats spend only a small fraction (~ 5%) of their time in the euphotic zone, where biological growth inside the conductivity cell can cause sensor drift; and the use of a biocide inside the cell effectively stops the small amount of biological growth that might be possible in the deep sea.

The results from recovered floats strongly suggest that the salinity data from Argo floats are of a quality commensurate with the targeted accuracy. On the other hand, floats are not generally recovered, and most floats are last seen when they are deployed, even though they continue to operate in the ocean for many years. Thus, it is necessary to find other measures of the quality of salinity data from individual floats and the ensemble as a whole. One measure of the quality of salinity data is the accuracy of the calibration of the sensor just prior to float deployment.

Each SeaBird CTD undergoes extensive factory calibration prior to being shipped to various laboratories around the world, and the manufacturer claims a salinity accuracy of 0.005 for these sensors when they leave the factory. To check the accuracy of sensors prior to deployment, we initiated a test in University of Washington laboratories to compare the salinity sensor on each float's CTD immersed in a bath against the measured salinity on a known, standard SeaBird sensor in the same bath. The standard CTD is regularly recalibrated at SeaBird, a straightforward procedure due to the proximity of SeaBird and the University of Washington. This test is really a comparison, not a calibration, as we cannot duplicate the extensive calibration facility at SeaBird; but the comparison is a very quick way to assess the quality of the calibration of each CTD prior to deployment. In general, the results from several years of these comparisons (Figure 3a) show that the measured salinity values on nearly all CTD units agree with the value measured by our standard CTD to within 0.005 at the time when the floats leave the University of Washington, destined for various deployment locations around the world. From this, we can be reasonably confident that the floats meet

TABLE 1. Properties of four Argo floats recovered and recalibrated at the factory after extended periods in the water. The Japanese float data were taken from Oka (2005).

FLOAT	TIME (days)	ΔT (°C)	ΔS (PSS-78)	Δp (decibars)
29045*	840	0.00136	-0.0074	4.68
2900056*	730	0.00158	-0.0074	5.92
29051*	900	0.00100	-0.0125	0.72
41862†	1096	0.00030	-0.0060	0.06

* Deployed by Japan in the North Pacific † Deployed by the US in the North Atlantic

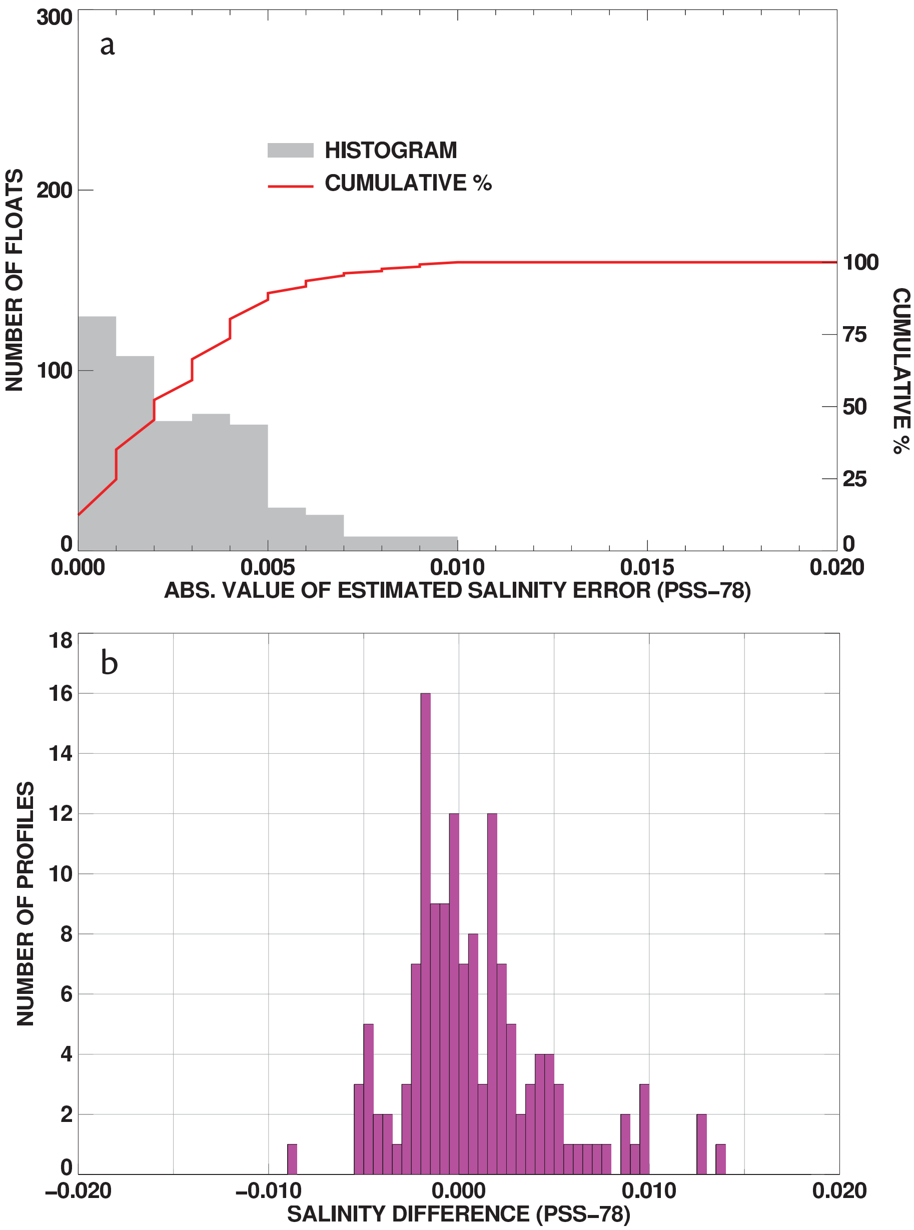


Figure 3. (a) A histogram of the absolute value of the difference in salinity between a known salinity standard (a well-calibrated SeaBird CTD unit) and CTD units on 480 Argo floats constructed at the University of Washington between 2002 and 2006. (b) A histogram of the difference in salinity on the 2.4°C potential temperature surface between shipboard CTD stations collected in the South Pacific by the Japanese vessel *Mirai* in 2003 and 142 Argo floats located within 100 km of the *Mirai* stations and within one year in time. The blue line in Figure 1b shows *Mirai*'s track in the South Pacific.

the Argo target accuracy for salinity when they are deployed.

Another measure of salinity-data quality from Argo floats is the comparison of float-derived salinities with nearby high-quality shipboard CTD data. For this comparison to be useful in an era when the ocean is undergoing many changes in its properties, it is necessary for the float and shipboard data to be approximately coincident in time. An excellent opportunity for such a comparison occurred in 2003 in the South Pacific, when the Japanese research vessel *Mirai* was collecting CTD data along a section at 32°S that repeated a WOCE section occupied 11 years earlier (blue line in Figure 1b). In this study, salinities on the 2.4°C potential temperature surface from shipboard CTD casts were compared to the measured salinities at 2.4°C from floats within 100 km in space and one year in time of the ship-based data. In all, 142 float/shipboard data comparisons were possible using the *Mirai* data; Figure 3b shows a histogram of the results. The salinities measured by the two independent methods agree quite well, with an overall mean difference of 0.002 and a standard deviation of about 0.004. The nature of calibration error on the float CTD is such that the salinity errors at all levels of the water column tend to be *the same*; thus, we can assume that the salinity errors at other levels of the water column are of a similar magnitude.

From the outset, it was planned to deliver Argo data in two streams. In the first stream, raw data are available in near-real time from various national and global data centers. In the second stream, Argo salinity data are subjected to *delayed-mode analysis*, where they are compared in detail with historical data from a number of sources at intervals of several months to assess the stability and time dependence of drift of the salinity sensor on each individual float. Once the sensor drift has been determined in some time interval for a float, the raw data are then adjusted so as to remove the error induced by sensor drift. To ensure that the global Argo data are self-consistent, all Argo participants have agreed to use common reference data sets and software tools for making these comparisons and adjustments (Wong et al., 2003).

The delayed-mode results for the first several years of floats deployed by the University of Washington (and, by inference, similar instruments that have been deployed by other float groups) show remarkable stability in salinity measurements over extended periods after deployment. For the first ensemble of 391 floats analyzed using the delayed-mode tools, only eight instruments (~ 2% of the group) required any delayed-mode salinity adjustment in excess of 0.01. In most cases, we opted to apply no delayed-mode adjustments smaller than 0.01 to the data, in recognition of the fact that surely the errors in the reference data set are at least as large as this threshold. The floats comprising this ensemble had been in the water from periods of less than one year to more than six years, with the number of floats requiring salinity adjustments roughly the same in each year class. A more recent examination of a larger ensemble of floats using delayed-mode analysis, where floats having both salinity and pressure-offset errors were examined, suggests that eventually somewhere between 5–10% (still a remarkably low fraction) of the Argo data will require some form of delayed-mode salinity adjustment in excess of 0.01. These heartening results bode well for the future of long-term ocean salinity measurements.

Thus, we have four independent tests that can be used to assess the quality of salinity data from Argo floats. The pre-deployment comparison of float salinity sensors to a known standard (Figure 3a) attests to the quality of the sensors just prior to deployment, and the delayed-mode analysis confirms the long-term stability of the float salinity measurements after many years in the water. The delayed-mode results are completely consistent with the few results from floats recovered and recalibrated after several years in the water (Table 1). And, the comparison of high-quality shipboard CTD data from the South Pacific with nearby Argo float data (Figure 3b) shows that float data agree well with shipboard data collected using a recently calibrated CTD system, where salinity quality is determined using a highly accurate salinometer and standard seawater. Taken together, these independent checks suggest that the salinity data collected from the vast majority of floats are accurate to about 0.01 over several years, and that raw data from most of this ensemble require no correction and are nearly good enough to be considered final data. In spite of this success, however, all of the checks and comparisons built into this system for each float must continue, because problems could arise with new batches of sensors or float hardware at any time. The results so far have been extraordinary, but vigilance is still required, and the collection of high-quality data from floats is still far from being routine.

LARGE-SCALE SALINITY YESTERDAY AND TODAY

In recent years, changes in the ocean's properties have been widely reported and discussed, including surface-to-bottom changes in both the large-scale ocean and marginal seas. Examination of such changes in the oceanic environment is relatively new and is made possible by the increasing quality and quantity of oceanic data that became available during the second half of the past century. Although a large quantity of salinity data was available to the research community prior to WOCE, the quality of these data was highly variable and generally poorly documented. During WOCE, there was a great deal of emphasis on obtaining the highest quality of data possible, so that future generations of scientists would have a benchmark of the state of the oceans during the 1980s and 1990s. Now, some 20 years after the beginning of WOCE, Argo represents the next generation of global ocean experimentation, with true real-time, global coverage of the upper 2000 m of the world ocean.

Here, we inquire into whether decadal-scale differences in ocean salinity can be discerned by comparing these two data sets. In particular, we examine a single, exceptionally long section in the Pacific Ocean, WOCE P15 (red line in Figure 1b), which extends nearly from the northern edge of the open Pacific (the Aleutians) to the seasonal ice zone in the Antarctic. The section was carried out in three parts, beginning with the northernmost (north of 20°N) and central (20°N–15°S) portions of the section early in 1994, and ending with the southernmost part (15°S–65°S) early in 1996.

As the top panel of Figure 4 shows, the section encompasses the entire range of salinity regimes in the central Pacific Ocean. At high latitudes in both hemispheres, low-salinity water at the sea surface is evident, with this water penetrating the ocean interior as tongues of low-salinity intermediate water both north (as North Pacific Intermediate Water) and south (as

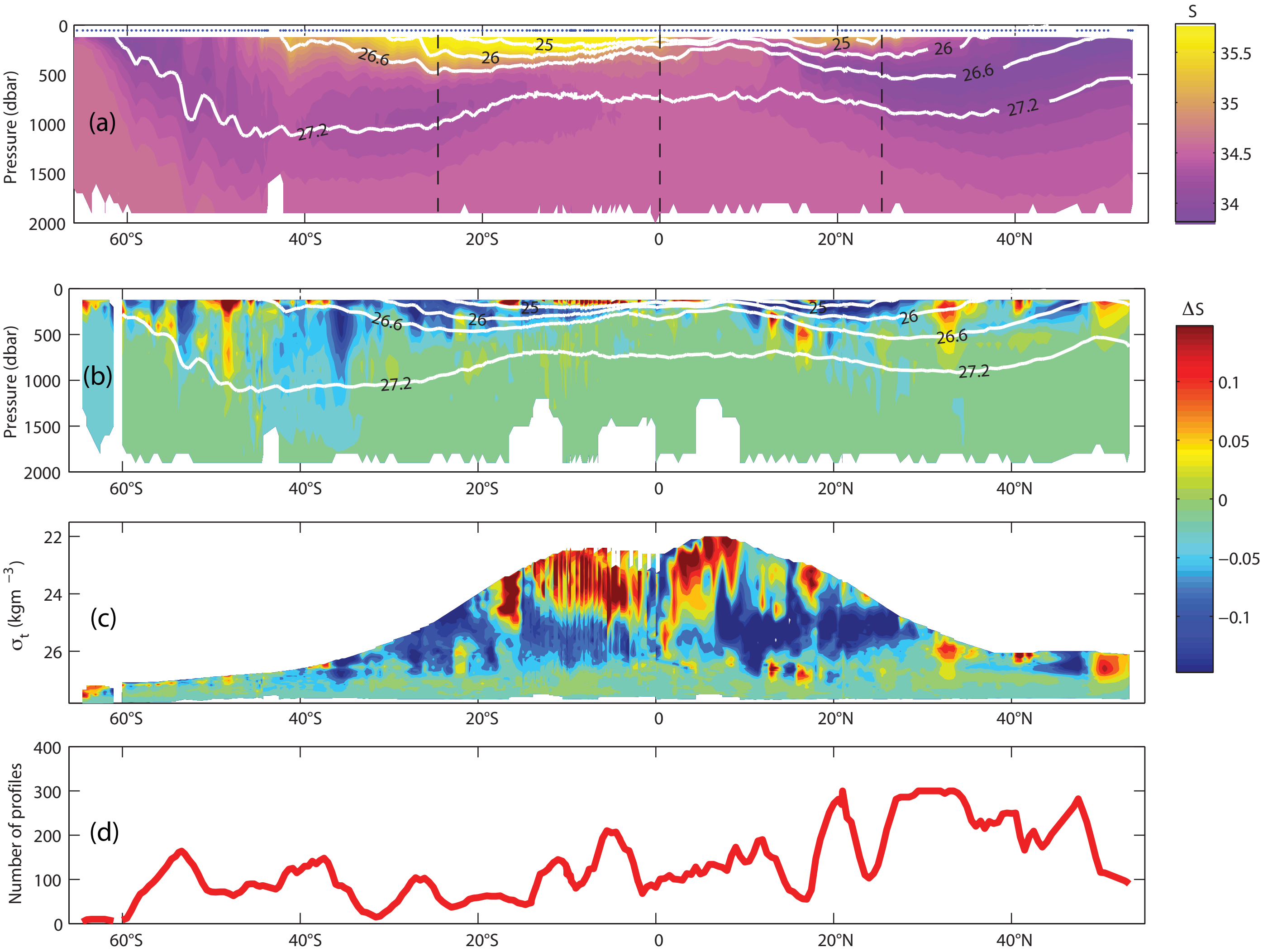


Figure 4. (a) Salinity as a function of latitude measured in samples collected along WOCE section P15 (red line in Figure 1b) during late 1994 and early 1996. Blue dots along the top of the section indicate station positions. (b) The difference in salinity between shipboard data collected along WOCE P15 (the data shown in (a)) and Argo floats from 2004–2006 mapped to the WOCE station positions as a function of depth, computed as described in the text. The plot shows contours of density (σ_T). (c) Same as for (b), but plotted on σ_T surfaces. (d) The number of profiles used in estimating Argo salinity at each WOCE station position.

Antarctic Intermediate Water) of the equator. Below these intermediate water masses lie the central waters of the Pacific and the uppermost part of Pacific Deep Water. In the subtropics, ranging from about 30°N to 40°S, relatively high-salinity water is found in the upper ocean, presumably the result of a large excess of evaporation over precipitation at these latitudes. Of course, such a section is only two-dimensional, so many features seen in the section are likely attributable to conditions elsewhere in the Pacific, away from the P15 line.

While the uniform quality of the WOCE and Argo data sets would seem to make them compatible for comparison, by nature the methods of data collection were quite different. The WOCE data were collected once, along a fixed line, at intervals of about 50 km and at roughly 2-m depth intervals over the entire water column. The Argo data are collected at random locations statistically 300-km apart, with about 70 unequally spaced observations between the sea surface and 2000 m. Thus, some work was required in order to make the data sets compatible, and the process of comparison required several steps. First, each WOCE station was subsampled at the depths of the Argo observations (most floats collect data at standard depths that vary by only a few meters from instrument to instrument). Second, the Argo data were mapped onto the positions of the WOCE sections. This was done by selecting all Argo data within an ellipse encompassing 3° of latitude and 5° of longitude centered on the position of each WOCE CTD station, then objectively mapping these Argo data to the WOCE position using a 300-km Gaussian correlation function. The difference in salinity at each of the Argo depths was then computed by subtracting the vertically subsampled WOCE salinity data from the mapped Argo salinity at each station location and depth. Argo data from the time period January 2004 to December 2006 were used in this calculation, and in most cases over 100 Argo profiles were used in creating the objectively mapped Argo average at the WOCE positions, (bottom panel in Figure 4).

The results of this comparison reveal significant, measurable, large-scale changes in upper ocean salinity in the decade following the mid 1990s. The second panel in Figure 4, showing the changes in salinity on pressure surfaces, indicates that most changes in salinity are confined to within 500 m of the sea surface, with changes penetrating deeper in the water column between 35°S and 45°S (only comparisons below a depth of about 200 m are shown here, below the local outcropping density, in order to remove seasonal differences between WOCE and Argo data from the calculation). The changes appear to be largest in the subtropical gyres in both hemispheres. The magnitude of the changes is sizable over much of the section, often well in excess of 0.05 and considerably larger than the estimated accuracy in the Argo measurements. Thus, these changes appear to be real and of nearly hemispheric scale. In most cases, the changes in salinity are negative (a freshening of the ocean over time).

On density (σ_T) surfaces (the third panel in Figure 4), an increase of salinity over time can be seen in the tropical upper ocean, within about 15° of the equator, with a large-scale freshening below extending to nearly 40° in both hemispheres. This freshening appears at densities as high as 26.6 in the north and about 27.0 south of the equator, with the freshening signal somewhat stronger in the north. Below densities of 27.0, there is little discernible salinity change anywhere along the section. Integrating the salinity differences along the section (Figure 5a) confirms that there is a net freshening (salinity decrease) in both hemispheres, confined to depths above about 600 m in the north and 800 m in the south. The other panels in Figure 5 reflect the changes in the temperature/salinity relation along the section that are implied by the salinity changes on density surfaces (see the dashed lines in the upper panel of Figure 4 for these locations): there is a clear freshening at temperatures above about 10°C (densities of 26.3) at 15°N and at temperatures above about 12°C (also a density of 26.3) at 15°S. Precisely at the equator, the temperature/salinity relation shows a freshening above 20°C and little change below this temperature, but an examination of Figure 4 indicates that near the equator the changes are highly variable in space.

These results appear consistent with the large-scale freshening of the subsurface ocean that has been observed in a growing number of studies. Dickson et al. (1988) discuss major anomalous salinity changes in the North Atlantic, and Read and Gould (1992) suggest that changes in Labrador Sea Water renewal between the 1960s and 1990s could account for the apparent decrease in salinity of 0.1 observed during that 30-year period. This phenomenon has by now been well documented and is treated in detail in the work of Dickson et al. (2002). In the Pacific, where deep ventilation is confined to high southern latitudes, the causes of subsurface salinity changes are more difficult to assess. Freeland et al. (1997) discuss the observed freshening and shoaling of the wintertime mixed layer in the Northeast Pacific after 1977, effects that are perhaps related to the Pacific Decadal

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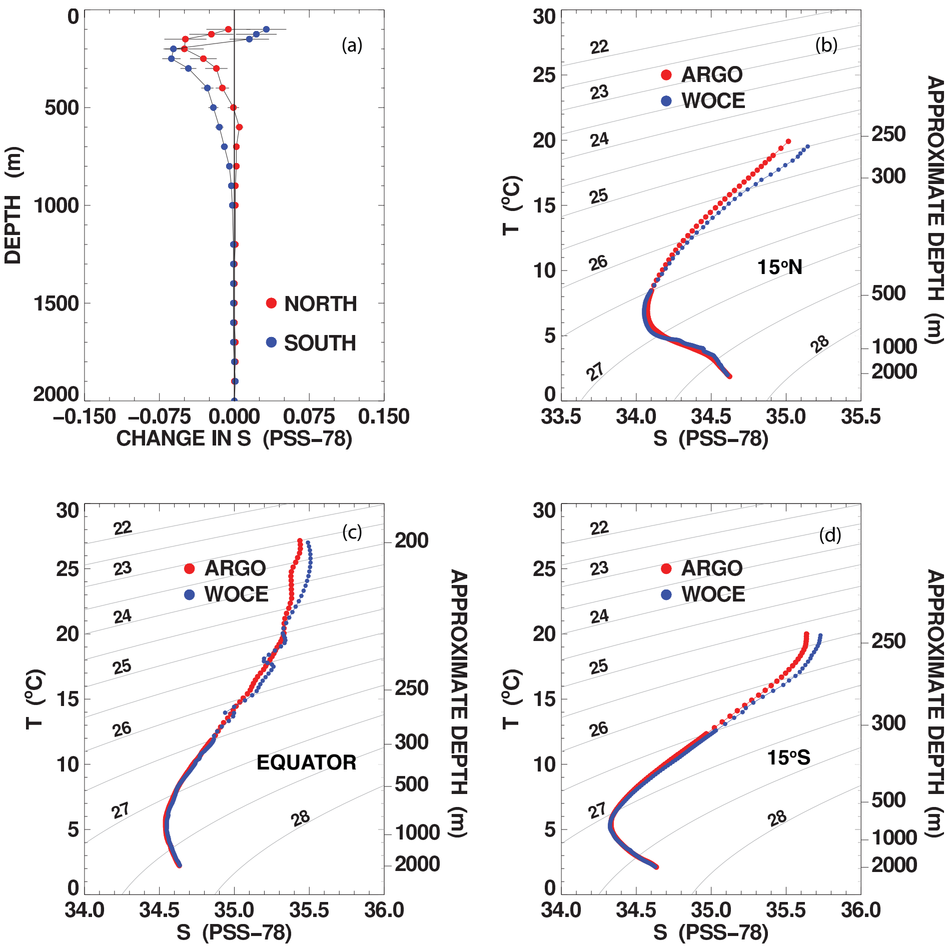

Figure 5. (a) Salinity difference between WOCE and Argo integrated along the P15 section as a function of depth for the northern and southern hemispheres. (b) The temperature/salinity relations for Argo and WOCE at 15°N. (c) The temperature/salinity relations for Argo and WOCE at the equator. (d) The temperature/salinity relations for Argo and WOCE at 15°S. The dashed lines in Figure 4a mark the locations of the stations shown in (b), (c), and (d).

Oscillation (PDO). Overland et al. (1999) document increased wintertime precipitation over the Northeast Pacific since 1977, also possibly attributable to PDO, potentially leading to freshening of the waters in the wintertime mixed layer that are later subducted and become subsurface water masses. This strong freshening in the Northwest Pacific might explain some of the freshening observed in Figure 4 between 10°N and 30°N: the waters at these latitudes are generally moving southwest, away from the North American coast, where they originate in the density range $\sigma_T \sim 25$–26 by subduction in springtime. Yet, the observed freshening is apparently not associated only with near-boundary phenomena: Lukas (2001) notes that near Hawaii there has been a pronounced decadal-scale freshening of the waters between the mixed layer and the thermocline since the early 1990s, apparently related to remotely forced, PDO-driven changes in precipitation elsewhere in the basin (see the article by Lukas and Santiago-Mandujano, this issue). The changes in salinity seen in Figure 4, however, are apparent in the Southern Hemisphere as well and extend to density surfaces that are not likely directly affected by PDO-type effects but are instead the result of changes in the large-scale hydrological cycle.

The WOCE-Argo comparison shown here is consistent with earlier studies comparing WOCE data with the historical database, and large-scale salinity changes were observed. The works of Wong et al. (1999 and 2001) indicate a large-scale freshening below the sea surface in both the North and South Pacific Oceans. These studies were conducted along zonal sections between 47°N and 43°S, with the freshening generally largest above densities of 27.2, roughly consistent with the results shown in Figure 4. In the North Pacific, densities in excess of 26.6 do not outcrop at the sea surface, and indeed Figure 4b shows that most of the freshening north of the equator is confined above this density. At high southern latitudes, densities as high as 27.2 can outcrop in winter, and changes in salinity on this surface can be seen in Figure 4; the properties on this surface in the southern hemisphere are determined by precipitation, evaporation, and ice formation and melting. Beyond pure freshening, the upper ocean waters near the equator shown in Figure 4 indicate an increase in salinity, which was also apparent in the works of Wong et al. (1999 and 2001). The entire pattern would appear to be possibly consistent with a strengthening of the hydrological cycle at the very largest spatial scales in the ocean, with increased evaporation and upper ocean salinity at low latitudes, and increased precipitation at higher latitudes, yielding lower salinities.

Manabe et al. (1990), for example, suggest that a greenhouse-induced warming of Earth's climate might result in a change in evaporation and precipitation patterns such that the near-surface salinity of the global ocean would increase at low latitudes due to increased evaporation as a consequence of the warming, with a decrease in surface salinity at higher latitudes resulting from increased precipitation. Although a demonstration of cause and effect remains to be shown, the distribution of salinity changes in the past decade shown in Figure 4 do not appear to be inconsistent with such a suggestion. Meridionally averaged salinity changes shown in Figure 5a are equivalent to the net addition of about 9 cm/yr of freshwater between 1995 (the mean year of the WOCE P15 observations) and 2005 (the mean year of the Argo data used) for each hemisphere. These estimates can be compared to the Manabe et al. (1990) model results (their Figure 20) of approximately 4 cm/yr of excess evaporation between the equator and 15°N, a net increase in precipitation of 1–2 cm/yr between 15°N and 60°N, and 4 cm/yr of excess precipitation between 15°S and 50°S. The model results were based on 60 years of a coupled ocean-atmosphere simulation, where the atmospheric CO_2 concentration was doubled at the onset of the run. This scenario would appear to be quite different from the comparison of two estimates of salinity along the P15 line 10 years apart, although the order of magnitude of the changes in the model and the observations are similar.

Eventually, more examples of decadal-scale salinity changes between WOCE and Argo will be examined, and surely there will be extensive modeling efforts aimed at understanding the changes in the global freshwater cycle in response to increasing greenhouse gas concentrations in the atmosphere. In a few years, the Aquarius satellite will provide global estimates of ocean-surface salinity on weekly time scales, complementing the subsurface measurements that Argo will continue to collect. In the past decade, it appears that there have been sizable changes in the upper-ocean salinity field of the Pacific Ocean. In another decade, when additional high-quality observations are likely available, there is room for hope that we can begin to understand such changes.

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