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Report of the U.S. CLIVAR Salinity Science Working Group

To the
U.S. CLIVAR Phenomena, Observation and Synthesis Panel

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Executive Summary

The US CLIVAR formed the Salinity Working Group[1] in late 2005 in recognition of the role that the oceanic hydrologic cycle increasingly occupies in our understanding of climate and climate variability. The charter of the Salinity Working Group was to:

- Describe the value of ocean salinity in refining our quantitative understanding of the global water cycle; in governing the global ocean circulation and overturning circulation; and in investigating the spatial and temporal scales of climate variability (including trends).
- Identify the requirements and challenges for analyzing, observing, and monitoring salinity, as well as for valid numerical simulation of those processes critical for determining the ocean's role in transport and storage of freshwater.
- Provide guidance to NASA (and the international community) on observational and scientific activities that should be considered in advance of, and during, the Aquarius/SAC-D mission to improve the measurement, analysis, and utilization of salinity information for the purposes stated above.

As part of their activities, the Working Group organized a special session at the 2006 Ocean Sciences meeting followed by an international workshop at Woods Hole in May 2006. This report is the summary of the findings and recommendations arising from these activities.

Salinity has long been recognized as an indicator of the strength of the hydrologic cycle. The salinity differences created by evaporation and precipitation in different areas are large enough to lead to significant density variations, often as large as or larger than the density differences due to temperature contrasts. Thus, salinity has important dynamical consequences for oceanic currents and mixing processes that directly impact the ocean's ability to absorb, transport and store heat, freshwater and carbon dioxide. Many of these processes are not yet represented in climate models. The need to understand the role of salinity in the modulation of upper-ocean mixing in both tropical and high-latitude regions is increasingly recognized. Models suggest that expanded monitoring of salinity will improve climate forecasts on inter-annual to decadal timescales. Similarly, there is an opportunity to use the expanding network of salinity measurements to improve our understanding of the role of the global water cycle in the climate system. Since most of the water cycle occurs over the oceans, this is an extremely important knowledge gap to be filled by the oceanographic community.

The report reviews observed salinity variations by region and their relation to other climate trends. A highlight of this summary is the striking evidence for decreasing salinity in the subpolar North Atlantic as well as in the southern polar ocean on decadal timescales. In contrast, near surface salinity in the subtropics has been increasing, providing the best available evidence for a changing water cycle. Superimposed on these long term trends are considerable variability, some of which at least is related to changes in surface meteorology. The report briefly describes modeling activities, and then reviews the current observing systems. The report concludes with recommendations for enhancements to the observing system.

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[1] www.usclivar.org/ Organization/SalinityWG.html

Recommendations:
In response to limitations of the historical observing system we support the maintenance and expansion of the current *in situ* observing system, especially Argo and the Volunteer Observing Ship thermosalinographs. We recommend enhancements to the global observing system specifically directed towards improved estimation of sea surface salinity:

- Expand the Argo instrument suite to include Surface Argo Salinity Measurements (Upper 5-m sensor) to allow a more precise calibration of AQUARIUS.
- Support development and testing of sea surface salinity sensors for deployment on the surface drifters of the Global Drifter Program.

The research reviewed here highlights the importance of accurate estimation of salt transport across key passages. Current technology based on CTD sections or innovative combinations of glider and mooring technology may be developed for this task, perhaps as part of a comprehensive program to monitor other parameters such as carbon transport.

The launch of AQUARIUS SAC/D, as well as improvements meteorological observing systems and models, offers the scientific community a unique opportunity to step beyond monitoring and to attempt to constrain the complete surface atmosphere/ocean hydrologic cycle based on observations. We propose a control-volume-type process experiment in which a volume of the upper ocean would be closely monitored in a defined geographic region, as illustrated in Figure 12. Within this control volume a complementary suite of observing systems would be used to constrain the storage of freshwater and heat as well as the fluxes across the boundaries. A complementary modeling activity should provide the most rigorous test to date of the way in which our climate models handle hydrologic processes. Two types of oceanic regimes would be of interest for the geographic location of such an experiment. An evaporative subtropical gyre is of interest because precipitation, salt advection and eddy activity are weak, water properties are set for incorporation into the thermocline, and our observing systems and models are best able to quantitatively constrain the water cycle. Conversely, an experiment in a high precipitation tropical regime could potentially aid directly in improvement of seasonal to interannual forecasting.

Improved *in situ* monitoring and remote sensing capabilities for salinity have provided this generation with an opportunity to contribute significantly to understanding of the role of the ocean in the both the global water cycle and in climate system dynamics. The Salinity Working Group hopes that this report provides some motivation to exploit this opportunity.

1. Introduction

Sea water contains a variety of salts including chlorine (55%), sodium (31%), and sulfate (8%) with ratios that are nearly constant from place to place, but with composite concentration, or salinity, that varies more considerably in space and time throughout the world oceans. These variations of salinity[2] are attracting increasing attention due to their relationship to the global water cycle and their influence on circulation, mixing, and climate processes.

On land, cycles of drought and flood, reflecting fluctuations in the hydrologic cycle, have enormous human impact. Since the world's oceans harbor the bulk of the free water on our planet, while experiencing most of the evaporation and precipitation, they must play an important role in fluctuations of the hydrologic cycle as well (*Schmitt, 1995*). Within the ocean, changes in the hydrologic cycle alter the stratification and impact the oceans' ability to sequester and transport heat, carbon, and freshwater in ways that are only partially understood. Despite its importance, many uncertainties remain regarding the climatological oceanic hydrologic cycle and even more regarding its variability. Recognizing the implications of these issues and developments for the climate research program, U.S. CLIVAR formed a Salinity Working Group (www.usclivar.org/ Organization/SalinityWG.html) in late 2005 with the following charter:

- Describe the value of ocean salinity in refining our quantiative understanding of the global water cycle; in governing the global ocean circulation and overturning circulation; and in investigation of the spatial and temporal scales of climate variability (including trends).
- Identify the requirements and challenges for analyzing, observing, and monitoring salinity, as well as for valid numerical simulation of those processes critical for determining the ocean's role in transport and storage of freshwater.
- Provide guidance to NASA (and the international community) on observational and scientific activities that should be considered in advance of, and during, the Aquarius/SAC-D mission to improve the measurement, analysis, and utilization of salinity information for the purposes stated above.

As part of their activities, the Working Group organized a special session at the 2006 Ocean Sciences meeting. Additionally, an international workshop in May 2006 provided an additional opportunity for the community to provide input into a report responsive to the Working Group goals. This report is the summary of the findings and recommendations arising from these activities.

1.1 Climatological Freshwater Fluxes

The surface freshwater flux into the ocean is the difference between precipitation (P) and evaporation (E) plus continental discharge, the majority of which is from gauged rivers (R) or ice export at polar latitudes. While (P-E+R) estimates remain quite uncertain the broad features of the time mean freshwater flux are evident. Among the three ocean basins, the majority of

[2] Traditionally salinity was expressed in parts per thousand, mass per mass. In recent decades, salinity has been defined using the Practical Salinity Scale of 1978 (PSS-78) based on conductivity measurements for seawater from the North Atlantic. This nondimensional salinity scale is commonly denoted by (practical salinity unit). Details are provided in the "Special issue on the practical salinity scale 1978", IEEE J. Oceanic Eng., OE-5, 1980.

oceanic precipitation occurs in the Pacific sector. This influx of freshwater, primarily by atmosphere transport of water vapor across central America (Zaucker et al., 1994) is only partially balanced by evaporation, leaving a net 0.5Sv gain by the Pacific (1Sv = $1x10^6$ m^3/s, **Table 1**). The Atlantic basin more than compensates for this imbalance, with a net loss of freshwater of 1.16Sv. Thus, one of the distinguishing features of the atmospheric component of the hydrologic cycle is a massive transfer of freshwater from the Atlantic sector to the Pacific. In order to maintain the time-mean salinity of the ocean this transfer must be balanced by an equivalent transfer within the ocean of freshwater from the Pacific to the Atlantic. One consequence is the higher salinity of the Atlantic Ocean relative to the Pacific Ocean. It is evident from **Table 1** that discharges from most rivers represent a small perturbation of the oceanic hydrologic cycle.

Table 1 Some components of the global water cycle in km^3/yr and Sv ($=10^6$ m^3/s) according to *Baumgartner and Reichel (1975)* and *Rignot and Kanagaratnam (2006).*

Pacific Evaporation	212,655 km^3/yr	6.74 Sv
Pacific Precipitation	228,529	7.24
Atlantic Evaporation	111,085	3.52
Atlantic Precipitation	74,626	2.36
African Precipitation	20,743	0.66
N. America Precipitation	15,561	0.49
European Precipitation	6,587	0.21
Amazon River Discharge	6,000	0.19
Mississippi River Discharge	560	0.017
Greenland Glacial Discharge*	225	0.007

Within each ocean basin the net freshwater flux shows considerable spatial inhomogeneity (**Figure 1**). The tropics represent a net source of freshwater due to the presence of intense convective precipitation while subpolar latitudes have both extensive precipitation due to storms and reduced evaporation because of lower SSTs. In contrast, evaporation exceeds precipitation in the subtropics where subsidence in the troposphere means that surface winds are warm and dry, while clear skies lead to high values of surface short wave radiation and thus high values of SST. These high salinity subtropical regions represent the oceanic extensions of continental deserts. High values of evaporation are also found near the Gulf Stream and Kuroshio, whose high SSTs and dry continental air flows lead to high evaporation rates.

The uncertainties of net freshwater flux into the ocean are difficult to assess. While over land there are a several precipitation-related observing networks, e.g. rain gauges and radars, over the ocean there are few quantitative in-situ observations. Remotely sensed precipitation estimates (through optical, empirical, or radiative approaches) need to be calibrated, and sampling problems often necessitate averaging satellite estimates over long periods and/or large areas. Various state-of-the-art precipitation analyses differ by a factor of two or more in many regions over the ocean. Despite these shortcomings, high-resolution precipitation products (down to 0.25-degree horizontal resolution) are now being produced. These could be used to study ocean-atmosphere freshwater budgets if improved estimates (through observations and improved analyses) of the ocean component of the hydrological cycle were available. The relative paucity of evaporation observations and the uncertainties of currently employed empirical approaches lead to large uncertainties of evaporation products over the ocean (*Schmitt, 1999*). In the ocean the freshwater budget may be combined with salt conservation to form a salinity budget in which P-E+R acts as a surface forcing through its diluting effects and storage is directly observable through salinity measurements. A new era of ocean salinity measurements, along with improved ocean model capabilities could enhance our ability to address the more complete *global water cycle*, which could lead to constraining precipitation and P-E analyses and improved knowledge and predictions of ocean circulation (and the related ocean storage and transport of heat, carbon, and freshwater).

1.2 Sea surface salinity features and dynamics

Sea water salinity is not only an equation of state variable and hence an explicit regulator of ocean dynamics, but it is a sensitive indicator of the marine hydrological cycle. The salinity at the sea surface (SSS) is closely linked to the regional patterns of sea-air flux of freshwater. The stratification of the near surface mixed layer is homogenized by turbulent and convective processes. The salinity budget within this mixed layer has a surface source term associated with the diluting effects of freshwater or the concentrating effects of evaporation. This surface source of freshwater is balanced by the effects of horizontal freshwater divergence, entrainment flux across the base of the mixed layer, diffusive processes, and local storage. The addition of small amounts of freshwater lead to measurable changes in SSS. For example, the addition of 10 cm of freshwater to a 50-m thick mixed layer with initial salinity of 36 would lower salinity by a measurable 0.07. Thus, SSS is the marine equivalent of terrestrial soil moisture, while transport divergence is the analog of run-off.

Two complications in the structure of the mixed layer need to be borne in mind when trying to understand the impact of SSS changes on climate. In the tropics and subtropics the depth of water with well-mixed temperature sometimes exceeds the depth of water with well-mixed salinity. The region between the bottom of the isohaline layer and the bottom of the isothermal layer is called the barrier layer (*Lukas and Lindstrom 1991*). This name reflects the fact that the layer constitutes a barrier to entrainment of cooler thermocline waters into the surface mixed layer. Barrier layers can form through surface fluxes alone (more precipitation than evaporation) or through advection, when salty waters are subducted under fresher waters or fresher waters override salty waters, (*Sprintall and Tomczak 1992*). In addition, barrier layers can be advected preformed into a region, or grow through vertical stretching (*Cronin and McPhaden 2002*). Recently, the advent of the Argo array (www.argo.net) has allowed exploration of the global distribution of barrier layers seasonally from individual data profiles (*Sato et al.,2006*) revealing that they are thicker and patchier compared with previous estimates from climatologies.

When near-surface conditions are such that the isopycnal (constant density) layer is deeper than the isothermal or isohaline layers, the region below the isothermal or isohaline layer has been called a compensated layer (*de Boyer Montégut et al.,2004*). These compensated layers are likely formed as a result of advection, most likely in the many regions of the ocean where horizontal density compensation is strong (*Rudnick and Ferrari 1999*). Their effect on air-sea interaction is not well understood, but could be large since only a small amount of energy might be required to change SST significantly over a strongly compensated layer.

In much of the world oceans SSS is essentially a measure of mixed layer salinity. The time-mean distribution of SSS shows a clear positive relationship to net freshwater flux, with high salinities in the evaporative subtropics and reduced salinities in the rainier tropics and subpolar regions (**Fig. 1b**). However, horizontal advection by ocean currents also plays a role in determining the distribution of SSS. The surface salinity maximum is found north of the strongest evaporation regions in the eastern North Atlantic due to poleward Ekman transport driven by the northeast trade winds. A close comparison also reveals strong SSS decreases associated with the discharge plumes of major rivers such as the Amazon, Congo, and Ganges/Bramaputra. Similar patterns of SSS variability are evident in the annual cycle analysis of *Boyer and Levitus (2002)*.

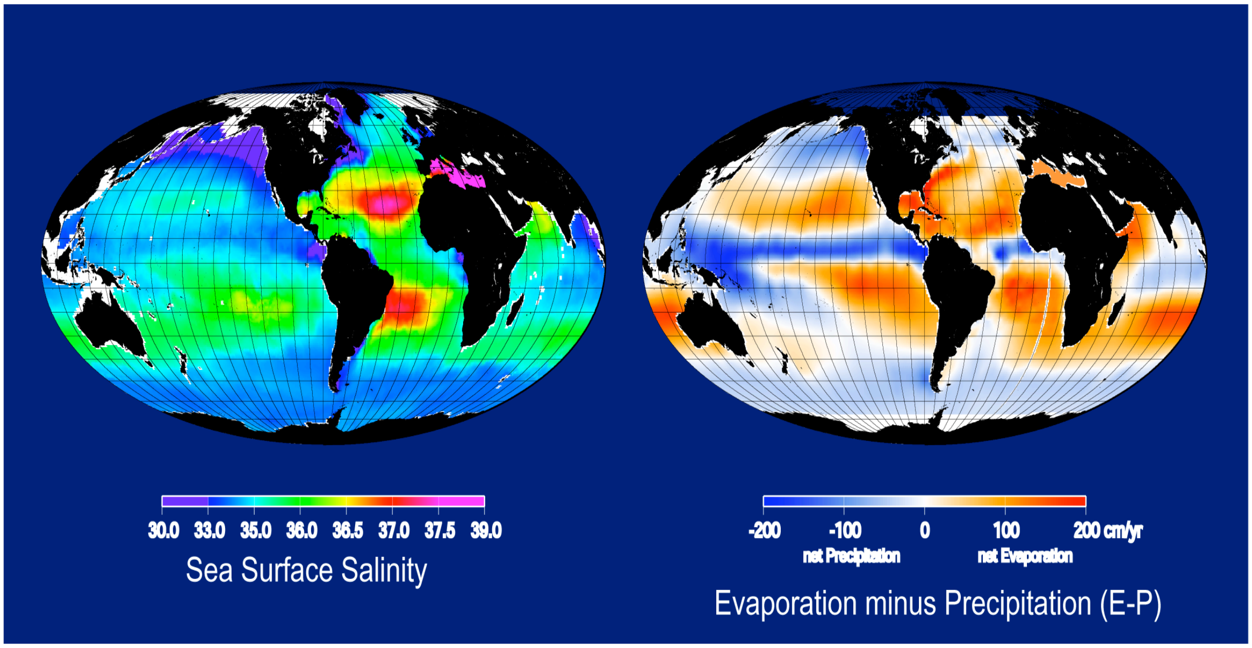


Figure 1. Global distributions of sea surface salinity (left) and net freshwater flux (right). The estimates of evaporation minus precipitation come from *Schmitt et al. (1989)* for the Atlantic and *Baumgartner and Reichel (1975)* for the other oceans.

2. High Latitudes

On the continental shelves around Antarctica the coldest, densest bottom waters, collectively termed Antarctic Bottom Waters (AABW), are formed (*Warren, 1981*). The next densest water mass is the North Atlantic Deep Water (NADW), formed by overflows of Norwegian Sea Water through gaps in the ridge between Greenland and Scotland. Formation of these waters represents the sinking limb of the global thermohaline circulation. Separating the thermocline regimes from the deep water is a layer containing low salinity intermediate water masses, most derived from the Southern Ocean, Antarctic Intermediate Water (AAIW). The global thermohaline circulation and closely related meridional overturning circulation, are critical elements of the ocean's ability to store and transport heat (*Ganachaud and Wunsch, 2003*) and carbon (*Ewen et al.,2004*). Improved understanding of these processes has gained urgency as it has become evident that the polar oceans of both hemispheres have been experiencing freshening both at the surface and at depth. While the upper layers of the tropical and subtropical ocean are stabilized by the temperature stratification, the upper layers of the polar ocean are stabilized by salinity stratification. Within the polar regions the potential for deep reaching convection and the resulting global thermohaline circulation depends on the delicate balance between the stabilizing salinity and destabilizing temperature profiles. Here we briefly review what is known about the time-mean and variable freshwater budget in the Arctic, subpolar North Atlantic, and Southern Oceans.

2.1 Northern Polar Region

The Arctic climate system, involving interlinked components such as the cryosphere, the ocean, and atmosphere (through the stratosphere), and is closely tied to the global climate system through the ocean, has been undergoing some major changes over the past 30 years (*ACIA Assessment, 2004*). Ocean salinity in the Arctic region reflects both the influence of changes in atmospheric circulation as well as the freshwater and heat flux exchanges between several of the Arctic system components. Estimates of Arctic Ocean salinity are incomplete; however, in some regions salinity has changed over the past 20 years. Some of this could be explained by changes in river discharge and precipitation. In other areas such as the Canada Basin, there has been no trend since the 1950s; however, a shift in storage of fresh water towards Canada may make more water available for export to the North Atlantic. The observing systems of the Arctic, which are focused along the Arctic's lateral boundaries, are inadequate for monitoring changes of the freshwater cycle within the Arctic, and consequently leading to considerable uncertainty in estimates of changes in other parts of the global climate system.

The subpolar North Atlantic is connected to the Arctic Ocean by a 1700 km wide opening extending from Greenland to Scotland. Across this opening there are two deep sills, the Denmark Straits between Greenland and Iceland with a maximum depth of 600m, and the Faroe Bank Channel between the Faroe Islands and Scotland with a maximum depth of 800m. The Canadian Arctic Archipelago has additional shallow openings to the Atlantic with depths less than 300m. The water masses of the Arctic Ocean are complex, reflecting a diversity of water formation processes. The lower depths are filled with Arctic Bottom Water with salinities around 34.95. Overflows of Arctic Bottom Water from the Arctic basin into the North Atlantic provide the source of the lower branch of the Atlantic thermohaline circulation, with additional deepwater formation in the Labrador Sea (*Gordon, 1986*). Above Arctic Bottom Water is the warmer Atlantic Central Water in the depth range of 150-900 m, but with similar values of salinity.

The characteristics of these water masses are not steady. The past 40 years have seen a freshening of the deep North Atlantic, reflecting a general freshening of the subarctic Seas. This freshening is evident in the salinity time series of *Dickson et al. (2002)* in **Figure 2**, which shows salinity decrease at a rate of -0.015/decade in many key channels. Estimates reported in *Curry et al. (2003)* suggest that the water north of 40^{o}N has freshened by 0.03 for the years 1985–99 compared to 1955–69. Recently this trend may have reversed (*Hátún et al.,2005*). Along the 24^{o}N meridian *Curry et al. (2003)* suggest the implied freshwater loss may be 5cm/yr averaged over 42 years. These changes have led to a shift in the temperature-salinity relationships in the North Atlantic (*Igor Yashayaev, Personal Communication*). At subpolar latitudes in the Pacific and Indian Oceans, *Ren and Riser (2006a, 2006b*) have also seen indications of freshening above the thermocline.

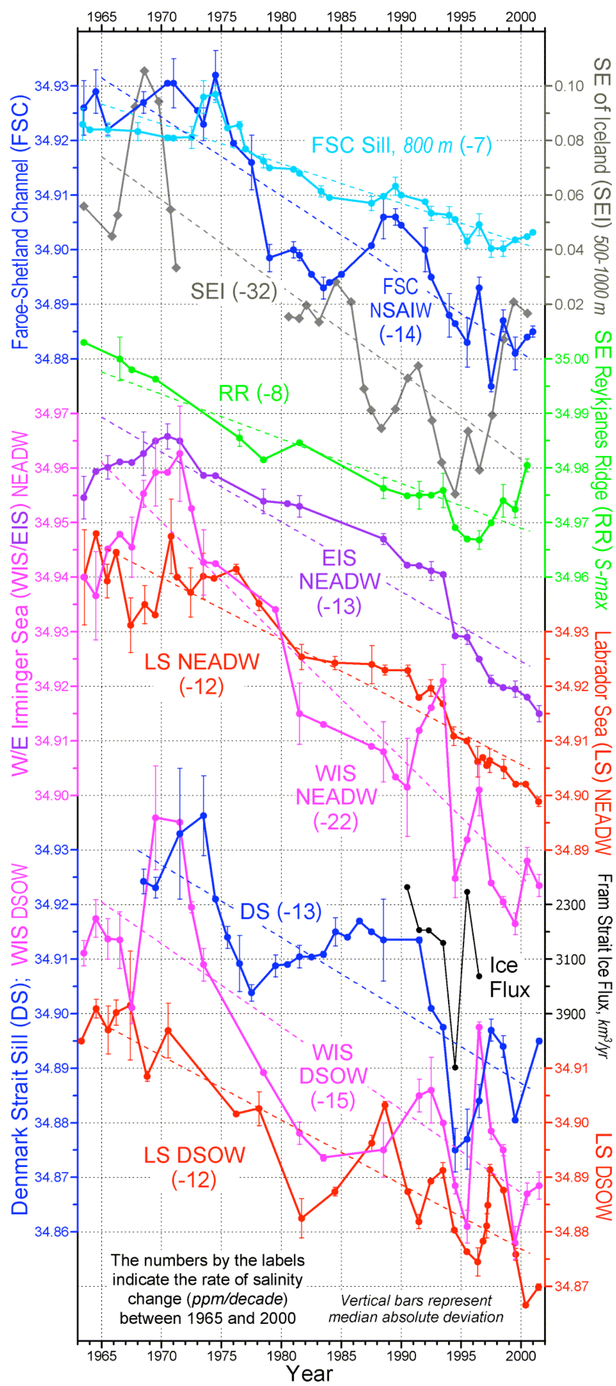


Figure 2 Freshening rates for a number of passages from *Dickson, et. al. (2002) "The salinity time series shown are plotted to a common scale (with the exception of SEI at half scale). The mean freshening rates in p.p.m. per decade listed against each curve are calculated for the common period 1965–2000, selected as the period of the most accurate salinity data set and the period during which the North Atlantic Oscillation (NAO) exhibited a sustained change between low-index and high-index extreme states. FSC sill and FSC NSAIW describe the freshening deep outflow through the Faroe–Shetland channel at sill depth and in the Arctic Intermediate Water layer, respectively. SEI shows the depth-mean anomaly of salinity in the 500–1,000m layer at the head of the south Icelandic basin, including data from the standard Icelandic Stokksnes section, and so represents the salinity of the water masses likely to be entrained into the eastern overflow as it leaves the Faroe Bank channel. (The short-term spike of the 'great salinity anomaly' of the mid-1970s has been omitted). RR represents the product of that mixing, describing the salinity trend in the deep salinity maximum which marks the core of ISOW against the deep eastern flank of the Reykjanes Ridge at 57–59°N, 27–31°W. EIS NEADW, WIS NEADW and LS NEADW describe salinity time series at successive stages in the spreading of the eastern overflow as it continues into the Irminger Sea, shoals and alters along the Greenland slope and ultimately forms the Deep Water of the Labrador Sea. Curves DS, WIS DSOW and LS DSOW describe the salinity trends of the Denmark Strait overflow at the sill (depths of 500–550m at T , 0 8C), in the 0–200m near-bottom layer where the overflow plume descends the slope off southeast Greenland, and in the abyssal layers of the Labrador Sea, respectively. The observed annual mean ice flux through the Fram Strait, 1990–97, is shown for comparison (scale inverted) as a possible remote cause of the enhanced freshening along this path in the mid-1990s." (Dickson, et al., 2002)*

Within the Labrador Sea, the entire water column has freshened to an extent such that by 1995 the equivalent of 6m of freshwater had been added over 40 years (**Figure 3,** and *Lazier, 1995*). Identification of the source of the anomalous fluxes of freshwater that support these salinity changes is an area of active research. Contributions from increasing Artic river discharges (*Peterson et al., 2002*) or increasing Greenland glacial melt (*Rignot and Kanagaratnam, 2006*) may contribute, but we note that a change in the E-P balance is a more likely explanation, since the volumes are so much larger (**Table 1**). Interestingly, since 2000 the region has experienced a weak salinification (**Fig. 3**).

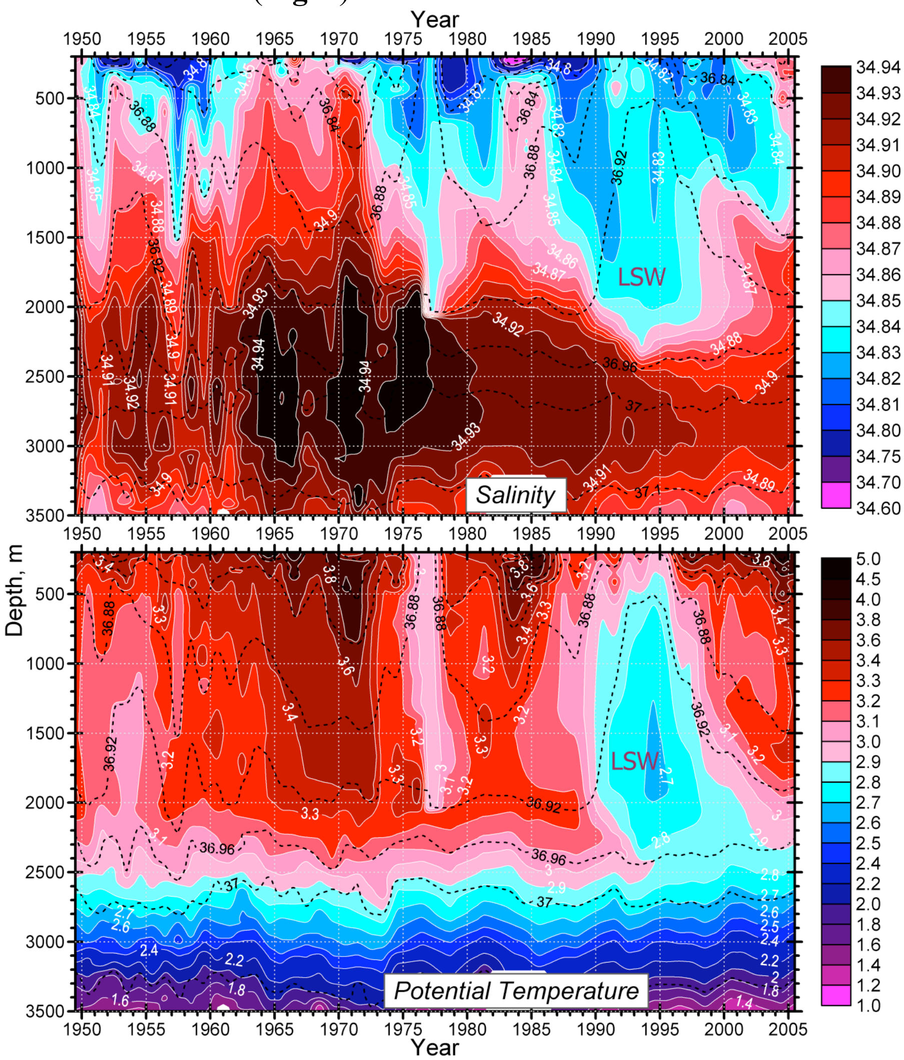


Figure 3 Changes of salinity (upper panel colors), potential temperature (lower panel colors) and potential density (dashed lines) in the Central Labrador Sea (*Igor Yashayaev, Personal Communication*). Note the decadal decrease in salinity followed by a weak rebound since 2000.

We next consider year-to-year variability. In this region near surface salinity is characterized by strong freshening due to the Great Salinity Anomalies in the early 1970s, early 1980s, and early and mid-1990s (*Belkin, 2004*), as well as freshening in the northern deep water formation regions (*Karcher et al., 2005*). The existence of the Great Salinity Anomalies appears to result from anomalous ice export from the Arctic Ocean. The episodic nature of the Anomalies complicates detection of long term salinity trends in near-surface waters. The relationship between sea ice export and winds in the subarctic North Atlantic suggests that changes in the strong North Atlantic Oscillation weather pattern in winter-spring may explain changes in SSS, although this issue is not settled. For example, examinations by *Furevik, et al. (2002)* and *Reverdin et al. (2002)* have come to different conclusions about this relationship.

2.2 Southern Polar Region

We next turn our attention to the Southern Hemisphere, the source of the densest of the global water masses, the very cold AABW, and of the relatively low salinity AAIW . Most of the water in the lower two kilometers of the global ocean is derived from AABW which is formed along the continental margins of Antarctica, notably in the Weddell and Ross Seas. This process represents one of the fundamental processes that overturn or ventilate the deep ocean, affecting the water column mean temperature and the sequestration of carbon within the deep ocean. AAIW is important in closing the freshwater budget of the subtropics by injecting low salinity water into the lower thermocline and forming the base of the thermocline in much of the world ocean.

The Antarctic Circumpolar Current, carrying some 130 Sv eastward (*Olbers et al., 2004*) serves as the primary deep water inter-ocean connection. Within the meridional plane, relatively warm, salty circumpolar deep water spreads southward and upward, entering into the ~100 m thick surface layer of near freezing temperature where it can interact directly with the polar atmosphere in the Antarctic zone south of the Antarctic Circumpolar Current (**Figure 4**). Recent estimates of the rate at which surface water is converted to the varied forms of AABW is ~10 Sv. Estimates of the contribution of Antarctic surface water to AAIW is less well defined, but one may assume from continuity that it amounts to the balance of the deep water input to the surface layer, about 10 Sv. The division between that part of the upwelling deep water entering into the bottom water versus that part which enters into the intermediate layer depends on the regional wind and freshwater input.

Complicating the freshwater budget of the Antarctic zone is the contribution of sea ice. With a salinity of about 20-30% that of the sea water from which it forms, sea ice represents a freshwater reservoir. Small amounts of net divergence of sea ice in a season overwhelms the local P-E. This effect has particular importance along the edge of Antarctica. There, as Antarctic continental air descends rapidly over the sloping ice sheet topography and within the confines of coastal valleys, it eventually encounters the ocean. The frigid air creates sea ice, but the associated high wind drives the newly formed ice seaward as fast as it forms, inducing a "coastal polynya", an expanse of sea water (typically 10-100 km wide) that remains directly exposed to polar air. As sea ice has markedly lower salinity than the water from which it forms, this "conveyor-type" process transports freshwater from the polynya region to the (remote) melting region, a process that overwhelms P-E. *Zwally et al. (1985)* conclude that the continued export of ice from coastal polynyas, "sea ice factories" that produce tens of meters of sea ice thickness per winter, is the primary factor in the production of salty freezing-point shelf water, which eventually leads to AABW.

Another important factor in the salinity budget of the polar ocean is the interaction of the ocean with the glacial ice composing the Antarctic ice shelves. The net effect of ocean-ice interaction is melting of the glacial ice and reduction of salinity, but at generally subsurface levels where the elevated pressure allows subtle thermobaric effects. These effects, combined with the lowering of the sea water freezing point at higher pressure, can lead in places to enhanced continental margin sinking associated with bottom water formation.

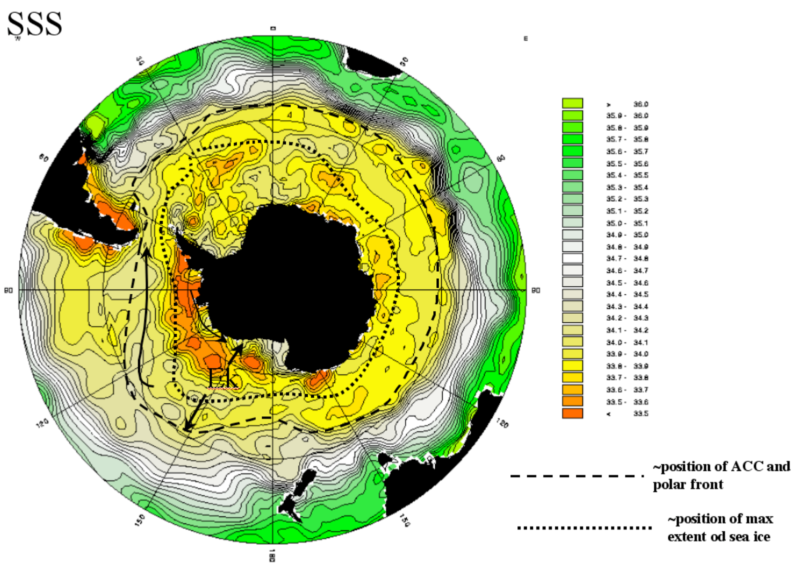


Figure 4. Sea Surface Salinity of the Southern Ocean (from the AWI Hydrographic Atlas of the Southern Ocean). Within the seasonal sea ice zone (poleward of the dotted line) Ekman transport is divergent in a region often referred to as the Antarctic Zone well south of the strong advection of the Antarctic Circumpolar Current (dashed line) so that surface layer residence time is < 3 years. Net upwelling into the surface layer amounts to ~24 x 10^6 m^3/s (*Gordon and Huber, 1990*).

We use the observational data set within the Antarctic Zone to investigate the variability of SSS within select regions within the Antarctic Zone (**Fig. 4**). The data set is sparse, but there is a discernable trend towards reduced SSS by perhaps 0.06 in the late 1970s. The relation is further investigated in the Weddell Sea and compared to changes in the Southern Annular Mode (SAM) (**Figure 5**). When the meteorological conditions reflect a positive phase of the SAM, SSS within the seasonal sea ice zone is decreased by excess P-E, leading to a more stable surface layer. When conditions reflect a negative phase of the SAM, the SSS increases, making the sea ice zone more susceptible to vertical exchange processes. This change in SSS has important effects on the ventilation of the deep ocean due to the weak stratification of the water column. It was likely the cause of the Weddell Polynya, a winter ice free area of 250 x 10^3 km^2 in the center of the Weddell Sea, near 65°S and the Greenwich Meridian during the mid-1970s (*Gordon, 1978, 1982*) was a breakdown of the pycnocline stratification brought about by reduced freshwater input to the surface layer. The breakdown resulted in deep-reaching convection that injected relatively warm deep water into the winter surface layer. Since then, the surface salinity has been reduced, strengthening the pycnocline (**Figure 5** and *Gordon et al., 2007*).

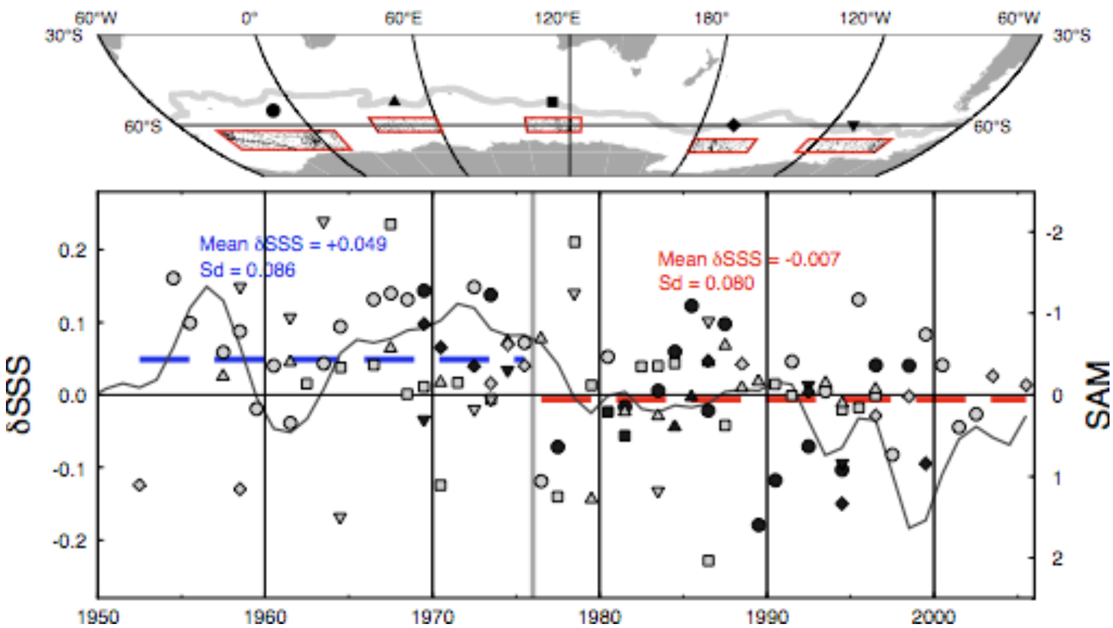


Figure 5 Time series of the anomaly of SSS (δSSS) relative to its climatological value with each of the red boxes; each box is represented by a different symbol. The thin grey line marks the year 1976 when SSS seems to have shifted towards lower values. The black dots have 5 or more SSS observations; the grey dots have 2 or more observations. The mean δSSS after 1976 is nearly 0.06 lower than the SSS prior to 1976. The Southern Annular Mode (SAM) index added (line, the scale along the right), as the SSS may be inversely scaled to the SAM.

Like its northern counterpart, a freshening trend is evident in the densest waters on the continental shelf of Antarctica. Shelf water salinity along the Adélie Coast has been decreasing from 1979 to 2001 (*Jacobs, 2006*). It has also been decreasing over the past four decades within the Ross Sea (*Jacobs et al., 2002*); in both cases as a result of changing fluxes including glacial ice melt. This freshening of shelf water is reflected in the freshening of bottom waters of the Australian-Antarctic Basin (*Whitworth, 2002; Rintoul, 2007*) and within the 2000-3000m layer directly seaward of the George V shelf (*Jacobs, 2006*). Changes in AAIW have also been inferred from salinity changes, as discussed in the next section of this report.

3. Subtropics

Owing both to a local excess of evaporation over precipitation and to a lesser extent the effects of surface advection, an SSS maximum is a prominent feature of every subtropical gyre (*Johnson et al., 2002*). Poleward of these maxima both salinity and temperature decrease, whereas equatorward of the maxima salinity decreases while temperature increases. These gradients set up a situation in which the large-scale meridional density gradients are much reduced from what would be expected from temperature alone (e.g. *Johnson 2006*). These temperature-salinity compensated waters are subducted in the eastern subtropics of most ocean basins and are classified as mode waters (*Hanawa and Talley, 2001*) because of their relatively vertically uniform temperature, salinity, and especially density. Subduction of these temperature-salinity compensated waters poleward of the subtropical salinity maximum injects variable water-mass properties into the subtropical thermocline. These anomalies have been observed in the western equatorial Pacific (*Kessler, 1999*), and in some numerical models they can reach the equator (*Yeager and Large, 2004*). Incidentally, if these anomalies do reach the equator and emerge at the sea-surface owing to equatorial upwelling, they may modulate phenomena such as El Niño (*Schneider, 2004*).

A subsurface minimum in salinity at 300-800 m depth occurs throughout much of the subtropical North Pacific and nearly the whole of the South Pacific. In the northern subtropics this is the North Pacific Intermediate Water (NPIW), formed in the Northwest Pacific by subduction (but not ventilation). South of the Equator, this is the cold and fresh AAIW, discussed earlier in the context of Antarctic Circumpolar circulation.

Several investigators have shown that there has been a large-scale freshening of the AAIW salinity minimum by as much as 0.05 in the southern hemisphere in data from repeated cruises a decade or more apart in time (*Johnson and Orsi, 1996; Wong et al., 1999; Wong et al., 2001*). The causes of these changes are not well-understood, but they are seemingly observed wherever enough quality data exist for a comparison across the decades to be made. The ubiquity of this result suggests a possible large-scale shift in the hydrological cycle on decadal scales at higher southern latitudes. *Wong et al. (1999)* estimate that the results could be explained by a 3 cm/yr increase in precipitation, well below the uncertainty in precipitation estimates. Based on an examination of Argo float data and earlier WOCE sections, *Wong et al. (1999)* and *Ren and Riser (2006b)* suggest the possibility of a similar freshening in the NPIW water of the subtropical North Pacific.

3.1 Salinity Variations in the Bermuda Atlantic and Hawaii Ocean Time Series

The two time series, the combined Hydrostation 'S' and Bermuda Time Series, BATS, in the subtropical North Atlantic and the Hawaii Ocean Time-series, HOT, in the subtropical North Pacific offer a unique view of salinity variations in these regions. The SSS data from BATS provides a remarkable record of fluctuations of SSS and implicitly of the sea-air freshwater fluxes from 1955 to the present. The weak advective (Ekman and geostrophic) field makes this time series a sensitive proxy for the regional marine hydrological cycle. Changes in SSS correlate to ENSO phase (**Figure 6**). During El Niño there is a reduction of SSS reflecting increased precipitation, which may be the seaward projection of the well-known positive El Niño-precipitation relationship in the southeastern United States. However, the El Niño-SSS relationship is robust only after 1976 (**Figure 6** lower panels) when the Pacific Decadal Oscillation (PDO) entered into a prolonged period of positive phase: the regime shift of 1976. Interestingly, we find the same shift occurs in El Niño-precipitation relationship.

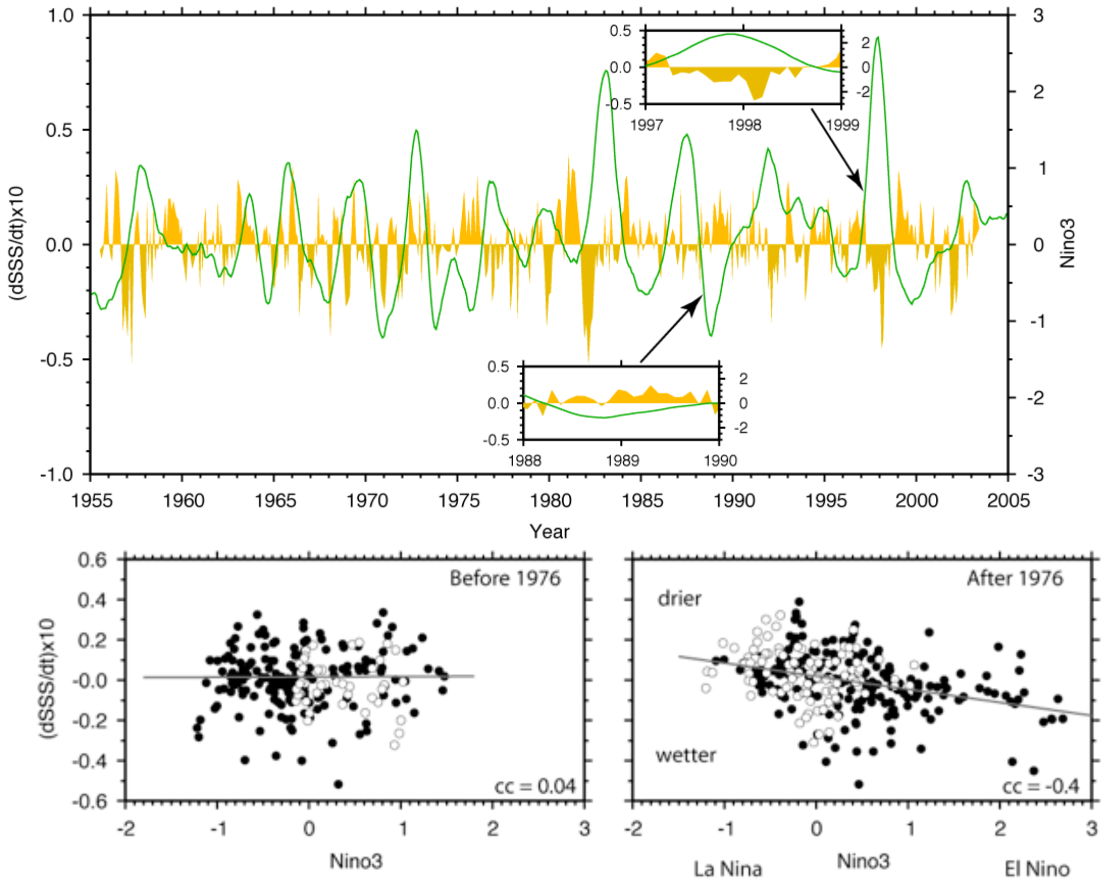


Figure 6 *Upper panel.* SSS (average of upper 20 m) rate of change x10 based on the 12-month running mean of monthly SSS BATS/Hydrostation S values. Lighter orange positive values (getting saltier) and darker orange those negative (getting fresher). In green, the 12-month running mean of the Niño3 Index. The two boxes in the graph display a period of decreasing SSS which corresponds to a strong El Niño event (1998) and increasing SSS corresponding to a strong La Niña event (1989). *Lower panels*. SSS rate of change versus Niño3 index (solid circles) for the period 1955-1976 (left) and 1977-2003 (right). The open circles show anomalous positive (negative) PDO during a negative (positive) PDO phase before (after) 1976. Correlation coefficients are indicated in the panels. (Gordon and Biulivi, 2007 in prep.)

Historically contemporaneous temperature-salinity measurements have been too sparse to monitor the formation of these salinity anomalies, much less their propagation, interannual variations, and decay. However, already with initial sampling from Argo, it has been possible to observe their seasonal formation (*Johnson, 2006*), which apparently may, because of their density-compensated nature, engender strong mixing through salt-fingering instabilities that could impact subsequent evolution of these anomalies. As the Argo float array reaches full sampling density, and is sustained over subsequent years, it should be possible to study the formation as well as the subsequent advection and modification of these anomalies by mixing and other processes.

The Hawaii Ocean Time series is located in the North Pacific subtropical gyre (22°45'N, 158°W). Water masses in the upper layers include North Pacific Central Water and NPIW, the later characterized by salinities below 34.4, a core depth of 500 m and seasonal variations of 0.05 (*Bingham and Lukas, 1996*). SSS at this location shows large variations, with values reduced by 0.3 during 1994-1997 and increased by up to 0.3 1998-2002. An investigation of the later anomaly by *Lukas et al. (2006)* suggests the elevated SSS resulted from a persistent rainfall deficit as a result of the confluence of effects of La Niña and the PDO. Together with the accompanying decrease in SST, the increase in SSS caused the density of the surface water to increase by 0.3 kg/m^3 and allowed the anomaly to extend throughout the upper 100m. At mid-pycnocline depth, in contrast, the water has freshened by 0.18 since 1990.

4. Tropics

The hydrologic cycle of the tropics is characterized by intense convective precipitation (with monthly averages exceeding 1.3 cm/day) together with high rates of evaporation, leading to strong gradients of SSS. Regions of high precipitation such as the western Pacific and Atlantic also commonly have salinity-stratified barrier layers (*Lukas and Lindstrom, 1991; Pailler et al., 1999*). The subsurface salinity fields in both the tropical Atlantic and Pacific show salinity maxima within the thermocline where warm, salty, subtropical water (frequently in excess of 35) is being transported equatorward as part of the shallow subtropical overturning circulation cells (*Kessler, 1999, Maes et al., 2002*). In the tropical Indian Ocean very warm salty water is introduced from the Red Sea and Persian Gulf to the north, and in the Indian Central Water to the south, while fresher water is introduced through the eastern boundary of the Indian Ocean basin (*Tomczak and Godfrey, 2001)*.

The surface freshwater fluxes in the tropics undergo substantial year-to-year variations, most prominently associated with ENSO in the Pacific and variations in the Indian southwest monsoon. Consequences of the changing fluxes, as well as the accompanying changes in advection, are changes in SSS in the range of 0.5-1.5 in the tropical Pacific (*Delcroix et al., 2005*). For example, SSS on the equator at 180^oW decreased by more than 1 in response to the El Niños of 1997 and 2002 (*Delcroix, 1998; Maes et al., 2006*). Barrier layers are common in the western Pacific, adding complexity to the ocean's role in ENSO (*Maes et al., 2006*). In the equatorial Atlantic SSS has a complex behavior, gradually increasing by 0.2 from 1960 to the late-1980s and then decreasing again in the subsequent decades (*Grodsky et al., 2006*). Here the decadal variations in SSS seem to be related less to changes in surface freshwater flux than to changes in entrainment associated with slow changes in the trade wind systems.

In the tropics major river systems link continental convective zones to the marine hydrologic cycle. In the Indian Ocean the rivers flowing into the Bay of Bengal affect the development of salinity-stratified barrier layers and may be a factor in the growth of tropical cyclones. Similarly in the Caribbean Sea and tropical Atlantic the Amazon and Orinoco River plumes spreading over the coastal ocean add stability to the surface ocean layer and thus indirectly affect the sea surface temperatures by reducing entrainment cooling of the mixed layer. As in the case of Indian Ocean cyclones, *Ffield (2007)* suggests a link between massive river export and tropical Atlantic hurricane maintenance and intensification.

4.1 Salinity and ENSO Forecasting

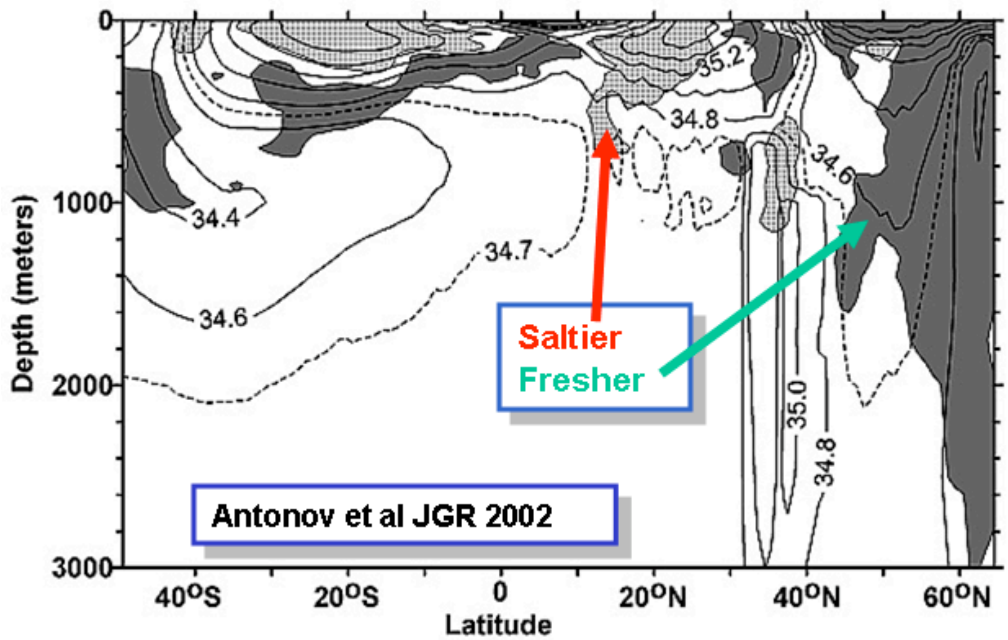
Studies such as *Vossepol and Behringer (2000)* have shown that that salinity effects need to be included even in tropical ocean models. This is particularly the case within the tropical mixed layer where salinity anomalies vary independently of temperature, allowing barrier layers to form (*Lukas and Lindstrom, 1991*). In the central-western equatorial Pacific where SST variations are reduced, SSS anomalies have correlations with ENSO approaching 0.7 and account for approximately 2 dyn. cm of the observed interannual height variations (*Delcroix and McPhaden, 2002; Maes et al., 2002*). *Ballabrera, et al. (2002)* take the next step and explore the potential contribution of SSS to ENSO prediction. They find positive correlations for lead times exceeding nine months with SSS anomalies between 5^{o}-10^{o}S. They suggest an overturning mechanism in which SSS anomalies can be subducted and eventually alter the stratification of the western tropical Pacific thermocline, thus influencing the evolution of ENSO.

5. Consequences of a Changing Climate

As noted above, observational studies of the sparse historical record reveal a freshening of the subpolar and wet tropical regions and salinification in the arid subtropical regimes. **Figure 7a,** (from *Antonov et al., 2002*) illustrates this with a zonally averaged meridional section of salinity trends over four decades. The light shaded regions have positive salinity trends, with a tracing of intermediate water formation and subduction evident in the subtropical latitudes. Freshening in the equatorial and high latitudes is clearly shown by the dark shaded regions, particularly in the northern hemisphere where the penetration is to at least 3000 m. These observed changes raise the interesting possibility that if conditions in the deep and bottom water formation regions changed such that a freshwater cap were formed, for instance by increased melting of the Greenland Ice Sheet (e.g. *Gerdes et al., 2006*), this cap might substantially modify the thermohaline circulation. At surface levels increases in salinity are evident in the subtropics, while the surface waters of the western equatorial Pacific are getting fresher (*Delcroix et al., 2007*).

These observed salinity trends bear significant similarity to Intergovernmental Panel on Climate Change AR3 and AR4 coupled climate model simulations of the 20^{th} Century changes (*Allen and Ingraham, 2002; Stouffer et al., 2006; Benthke et al., 2006*). The predictions of surface flux changes for the 21^{st} Century in **Figure 7b** from *Allen and Ingraham (2002)* likewise show continuing increases in tropical precipitation, especially the western Pacific, and drying of the subtropical gyres.

Globally averaged sea level elevation provides a way to track changes in oceanic freshwater due to melting of continental ice. Analysis of tide gauge data reveals a multi-decadal rise in global sea level of between 1-2mm/yr with a best estimate of 1.8mm/yr (*Miller and Douglas, 2004*). Of this, approximately 0.5mm/yr is due to thermal expansion of the oceans leaving approximately 1.3mm/yr eustatic rise due to melting of continental ice. Sea level measurements in the past twelve years have shown a more rapid rise, in excess of 3mm/yr (*sealevel.colorado.edu*). While this increase in the rate of sea level rise may reflect decadal fluctuations in the thermosteric component of sea level and not an acceleration of continental melting, direct observations of the ice sheets suggests there is little room for complacency. Studies in high latitude regions discussed above predominantly suggest freshening of the water column. Contrary to typical model assumptions, the added freshwater is not capping off the circulation but is being efficiently mixed to depth. By reducing the density of deep water this freshening has the potential to alter the rate of meridional overturning, and thus the ocean’s contribution to global heat transport. A better understanding of high latitude mixing processes is clearly required.



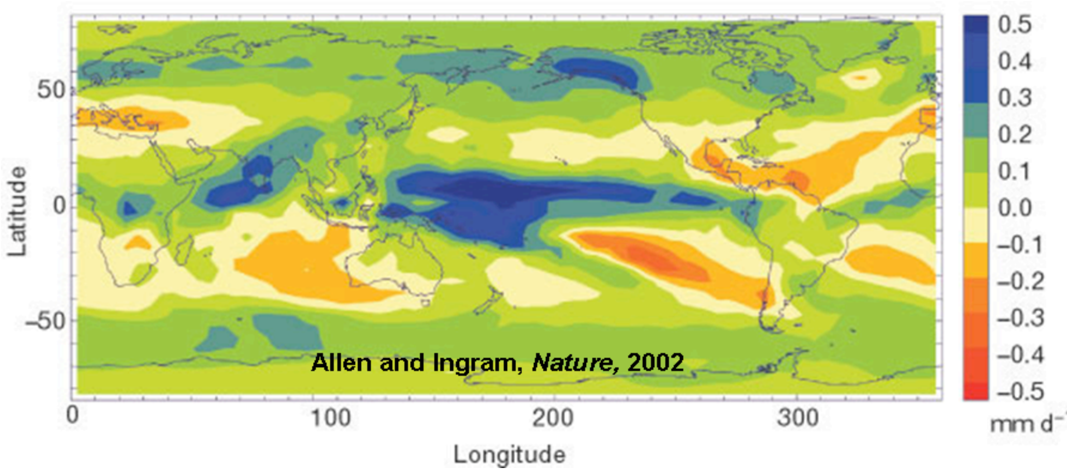


Figure 7a (top) Mean salinity anomalies zonally averaged over the world ocean for the 1978–1994 period (darker shaded areas, negative; lighter shaded areas, positive) superimposed on climatological mean salinity. Only anomalies that exceed 0.005 are shown. The zonal averages exclude values from the Mediterranean, Black, and Baltic Seas and the Hudson Bay. **Fig. 7b** (bottom) Precipitation change at the time of CO2 doubling averaged over all the members of the CMIP-2 ensemble for which data were available (14 models), for the 20 years centered on the time of CO2 doubling.

An additional implication of changes in the global salinity distribution, generally overlooked by physical oceanographers, is the potential change in the distribution of the partial pressure of CO_2 in seawater (pCO_2), owing to the fact that pCO_2 is a function of salinity as well as temperature and a number of other parameters. Changes in salinity and thus pCO_2 are likely to be accompanied by changes in the uptake (or outgassing) of CO_2 by the ocean at the surface. *Brewer et al. (1997)* note that a change in SSS of 0.3 will result in a change in the surface pCO_2 of about 10 μatm, approximately the same as the change in pCO_2 in the equatorial Pacific (an important region for ocean-atmosphere CO_2 exchange due to the large upwelling transport occurring there) during the 1990s as reported by *Takahashi et al. (2003)*. In the Takahashi study, the changes in pCO_2 were mostly due to changes in SST. Yet this SST variability was also accompanied by large-scale SSS changes of ~ 0.5 over parts of the North Pacific in the 1980s and 1990s. This is not to say that the pCO_2 changes noted by Takahashi and coauthors were caused by these PDO-related salinity changes, only that there exist large-scale decadal changes in salinity in the surface ocean of a magnitude large enough to affect pCO_2 and ocean/atmosphere CO_2 flux significantly. *Dore et al. (2003*) have likewise noted the pCO_2 changes associated with salinity variability at the HOT times series station.

6. Measuring and Monitoring

An *in situ* global ocean observing system consisting of a combination of several instrument types has begun to develop, both for the surface and subsurface ocean. Within two or three years this observing system will be augmented by data from two pioneering new satellite missions to provide global near-synoptic SSS mapping. These satellite and *in situ* observing systems will constitute an integrated salinity observing network that will meet the needs for scientific study of ocean salinities in the changing hydrologic cycle, and its role in ocean circulation and climate if it is sustained in the long term. In the tropics mooring arrays provide fixed observations despite strong currents. At select extratropical locations moored reference time series are also available. A global survey is provided by the newly deployed array of Argo floats, while CTD and bottle surveys are used for the abyssal ocean and in key locations. SSS monitoring is currently provided by the Volunteer Observing Ship program, and can be expanded in the future to include new techniques, including surface drifters, gliders and satellite remote sensing. Here we review each of these observing systems.

6.1 Moored Buoys

Moored buoys, platforms anchored in one small area, also offer opportunities for long time series of salinity. There are many coastal moored buoys. In the open ocean the TAO/TRITON array in the tropical Pacific consists of some 68 buoys. Of these, only one presently has more than one conductivity sensor with most of the data available only after 1995, while most have at least 11 thermistors deployed at depths down to 500 meters (**Figure 8**). The arrays have deployed salinity sensors at different depths over their history. The number of sensors at 125 meter depth is shown since this is the best covered subsurface depth in terms of salinity. The data records contain a number of gaps and the data require some post-processing.

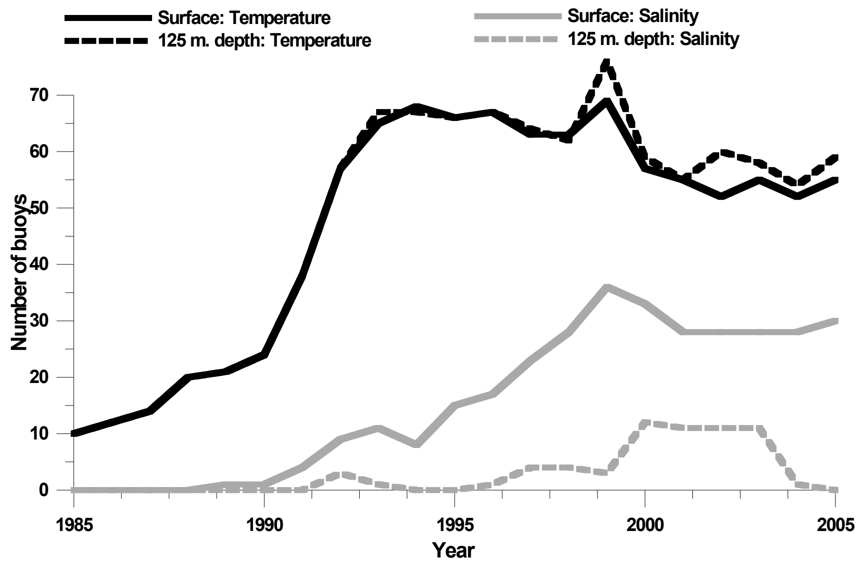


Figure 8 Number of TAO/TRITON buoys with temperature and salinity (conductivity) sensors by year. The present total number of buoys reporting ocean temperature or salinity is 68. The count for 1999 is > 68 due to switch from TAO to TRITON buoys in the western Pacific.

The tropical Atlantic supports the PIRATA array, which consists of 12 ATLAS-type moorings originally deployed in 1997 and expanded to 19 in 2006. These moorings have more conductivity sensors (1m, 20m, 40m, 125m), although the records have more gaps than their Pacific counterparts due to the less-regular servicing of the Atlantic moorings (*Foltz et al., 2004*). In 2005 several ATLAS-type modules were deployed on moorings in the Indian Ocean. More recent ATLAS modules include a Seabird conductivity cell specially designed for moorings. Prior to these modules, other Seabird conductivity cells were deployed. The required accuracy of the salinity measurements is 0.02, but achieving this accuracy requires regular servicing.

6.2 Profiling Floats

Profiling floats are autonomous vehicles that drift with the currents at a predetermined depth for a predetermined time before returning to the surface to communicate with a satellite, relaying oceanographic data (usually temperature and salinity) measured during the trip to the surface. Profiling floats cycle up and down in the ocean using changes in buoyancy (*Davis et al., 1992*; *Davis et al., 2001)*. The Argo project (www.argo.ucsd.edu), which started in 2000, maintains profiling floats to achieve complete coverage of the ice free global ocean excepting marginal seas and regions of depth less than 2000 meters and delivering the resultant quality controlled data in near real-time[3]. The floats have a lifetime of 4-5 years during which they will record salinity (and temperature) between 2000 meters depth and 5 meters depth every 10 days.

Most of the floats deployed so far carry SeaBird salinity sensors with a long-term accuracy of 0.01-0.02. *Oka (2005)* estimates a drift of -0.016 ± 0.006 over an expected four year lifetime based on three floats recovered after 2-2.5 years of deployment, and other recovered floats have shown similar results. The introduction of a biocide and near-surface shutdown of the CTD has helped ameliorate the problem of sensor drift (most Argo floats do not collect salinity data at depths shallower that 5 meters depth). Additional delayed-mode salinity corrections are made to

[3]The NEMO floats being used by Alfred Wegener Institute for Polar and Marine Research in the Weddell Sea might be extended around the Antarctic in seasonally ice covered areas. Similarly, Ice Tethered profilers like those being used by WHOI in the Arctic could be deployed in permanently ice-covered regions.

the data based on comparisons with historical salinity data (*Wong et al., 2003; Bőhme and Send, 2005*), with the final corrected data available within 6 months of collection. Another problem that can be corrected by a post measurement adjustment is due to differences between temperature in the conductivity cell and at the location of the thermistor used for temperature measurements. This cause an error of as much as 0.04 for Seabird 41 CTDs and 0.1 for Seabird-41CP CTDs when the temperature rate of change approaches 0.1°C s^{-1}, but algorithms are available for correction of this error (*Johnson et al., 2007*). Nearly half the total delayed-mode salinity profiles needed no adjustment. The majority of the remainder needed an adjustment of less than 0.01. The salinity measurements are generally very good for Argo floats.

Prior to Argo, the year with the most salinity profiles, based on the World Ocean Database 2005, was 1987. In that year, 63,575 distinct salinity profiles were collected, all from ship-deployed bottles and CTDs. The number of Argo profiles has rapidly increased (**Figure 9**) so that it surpassed this data count in 2005, collecting 69,498 salinity profiles. For profiles with measurements deeper than 1500 meters, the numbers are 10,596 bottle and CTD salinity profiles in 1987, compared to 33,341 Argo salinity profiles in 2005. Even though the counts in 2005 are similar to 1987 the geographic distribution of Argo is much more homogeneous (compare **Fig. 9a,b**).

The Argo project is now transitioning from startup to operational mode. Once the goal of 3000 floats is reached, possibly by the end of 2007, a global commitment to deploy around 800 floats per year should be sufficient to maintain the global array. A continued effort to insure that high quality salinity data are made available to the public is also an important component of Argo and is one of the key recommendations of this *White Paper*.

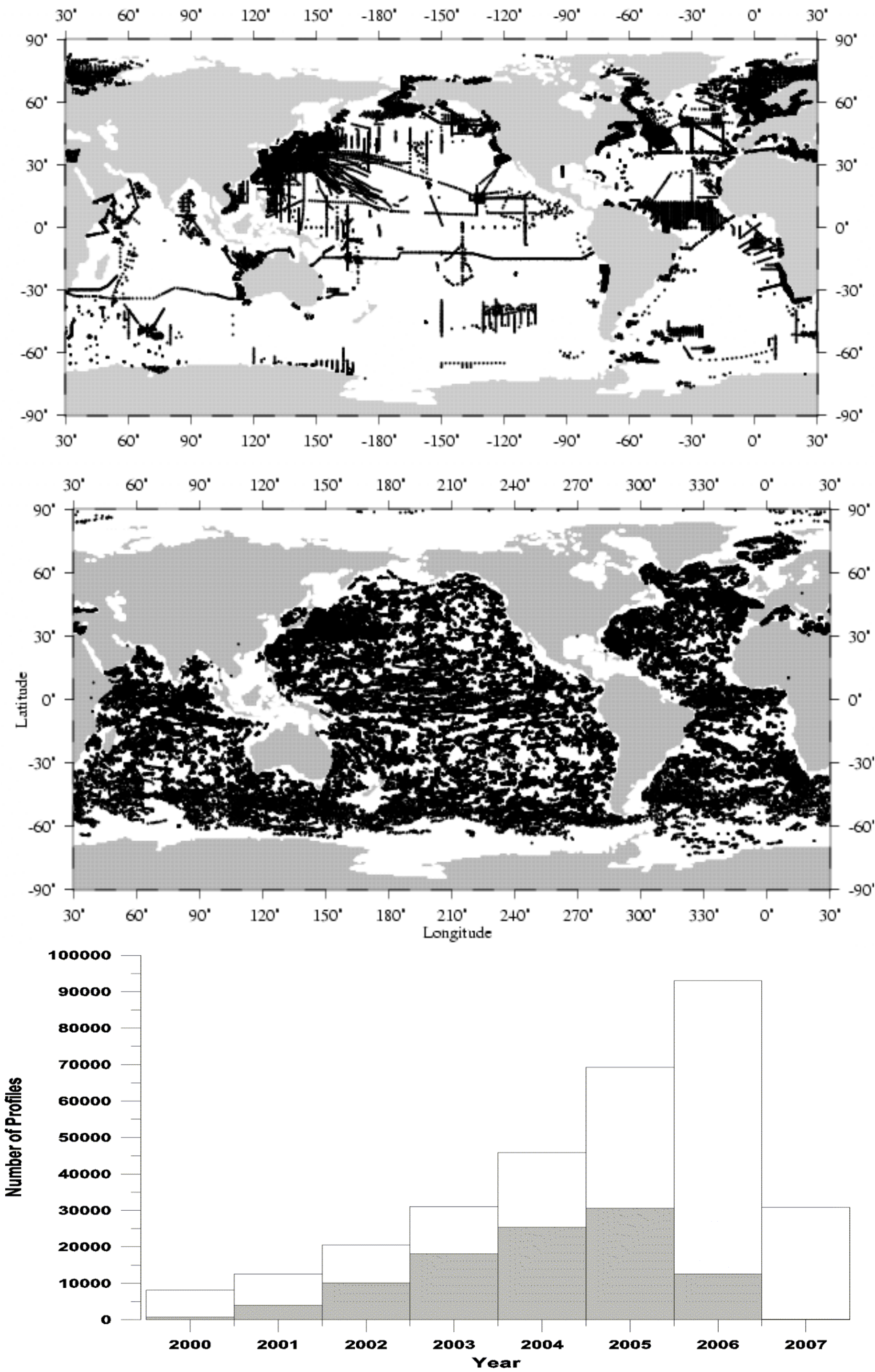


Figure 9. Geographic distribution of salinity profiles a) from CTD and bottle in 1987, b) from Argo profiling floats in 2005. c) Number of salinity profiles from Argo profiling floats, per year (through June 3, 2006). Shaded regions are number of fully quality controlled (delayed-mode) salinity profiles available by year.

6.3 Volunteer Observing Ship Thermosalinographs

Thermosalinographs (TSGs) have been installed on research vessels for at least 30 years, and have become wide-spread since the mid-1980s, with at least 50 to 100 TSG equipped vessels. Little of these data have been quality controlled and validated. Since the early 1990s, TSGs have been placed on Volunteer Observing Ships for projects dedicated to observing near surface salinity or carbon dioxide fugacity. The Global Ocean Surface Underway Data pilot project (GOSUD, www.gosud.org) has been set up to provide information on these and other TSG collection efforts.

The bulk of the instruments installed right now are SBE-21 TSGs. Some of them are equipped with a bubble trap and some not. Data are often reduced to one value per 1 to 5 minutes in order to remove some of the high frequency noise inherent in these systems. The experience acquired during the last 15 years indicates that the positioning of the instrument on the ship, the particular water circuit used (and pump), and the flow rate (and whether the TSG is exposed to extensive bubble activity), all have a large impact on the data return. Real time transmission has been implemented on some vessels, which allows quick detection of problems and thus improves the data return. The quality of the data has also been shown to depend on regular maintenance (cleaning) of the instruments, which should be done on at least on a monthly basis, and collection of water samples to analyze possible drifts due to instrumental fouling and correct them a posteriori. Obtaining a good-quality set of data (to within 0.02) from VOS is therefore quite personnel-intensive. Another difficulty encountered is that vessels sailing particular routes tend to be changed rather frequently, creating logistical difficulties, and often resulting in loss of data for at least 3 months after each change. Some of these data are now available in near-real time on servers (e.g., www.gosud.org). Additional information about the successful effort by the Laboratoire d'Etudes en Géographysique et Océanographie Spatiales (LEGOS) effort can be found at www.legos.obs-mip.fr/en/observations/sss.

6.4 Salinity Monitoring From Space

An important new capability for Earth observation and climate research is the pioneering development of salinity remote sensing satellite missions to be launched in this decade. These missions will provide global scale SSS analyses on week-to-month time scales and ~1^o spatial resolution, analogous to the resolution of the Reynolds and Smith (1994) SST analysis long used for climate diagnostics studies.

The European Space Agency SMOS mission, which is designed primarily to monitor soil moisture and secondarily ocean salinity, is expected to launch in 2008. It employs a complex phased array sensor the calibration of which is subject to significant uncertainty relative to the salinity signal. The joint United States/Argentina Aquarius/SAC-D, whose primary mission is to measure SSS, is expected to launch in 2010. To achieve the SSS measurement goals, Aquarius/SAC-D will employ the most precise and accurate satellite microwave radiometer ever developed for earth remote sensing. Both missions will have three to five-year lifetimes and both exploit the dependence of ocean surface microwave brightness temperature on SSS as well as SST (*Lagerloef, et al., 1995*; *Le Vine, et al., 2007*).

The Aquarius/SAC-D mission (see also aquarius.gsfc.nasa.gov) will fly in a polar orbit (98^o inclination) that provides global coverage every 7 days. The three-beam L-band polarimetric radiometer flies in a push-broom configuration with a swath width of 390 km and footprint sizes from 90-150 km. The data are intended for open ocean studies rather than coastal or estuarine investigations (> 450 km from coastal and ice boundaries); however, studies will be conducted to improve the SSS retrievals closer to the boundaries. The accuracy of this radiometer SSS measurement increases with increasing SST. Thus, while global monthly SSS anomalies of 0.2 will be detectible, the sensitivity of the measurements may approach 0.1 in the tropics and may be somewhat greater than 0.2 at high latitudes. The top panel in **Figure 10** shows an Ocean General Circulation Model simulated SSS field when sampled at the Aquarius/SAC-D footprint resolution and re-analyzed on a 1^{o} grid. The spatial resolution provides much more detail than can be obtained from an objective analysis of a random distribution of *in situ* stations in the bottom panel. Although the point measurements are substantially more accurate, they are more sparsely sampled and miss important spatial information. The comparison illustrates the power of integrated observations combining both the high spatial resolution of satellite observations and the accuracy and vertical profiling capability of *in situ* observations.

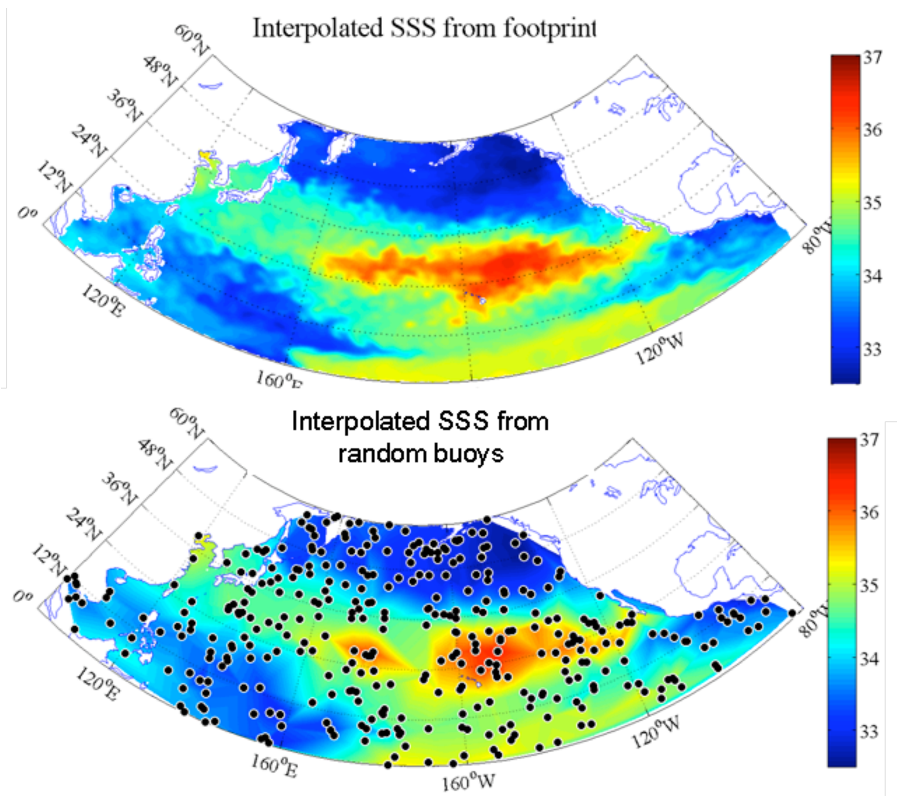


Figure 10a. (top) An OGCM SSS field sampled at the Aquarius/SAC-D footprint resolution and re-analyzed on a 1^{o} grid. **Fig. 10b** (bottom) Objective analysis of a random distribution of *in situ* stations in the bottom panel.

6.5 Future *In Situ* Enhancements

Thermosalinographs On Drifters The Global Drifter Program (GDP) now maintains an array of more that 1200 drifters distributed over the global ocean (www.aoml.noaa.gov/phod/dac/gdp.html) which provide an opportune platform on which to make near surface salinity measurements with conductivity-temperature sensors , Strategically deploying salinity sensors on a portion of this array can provide key new data for satellite validation, salinity budget calculations and other studies. The salinity data from these quasi-Lagrangian surface instruments will have the same advantages and inconveniences (with high temporal resolution and useful accuracy, dispersion and inhomogeneity of sampling) as other SVP drifter data. The idea was first developed during TOGA-COARE on 15m-current following surface drifters with an unpumped TSG system. This yielded satisfying results, although not fully qualified. After different attempts, new Surface Velocity Program (SVP) surface drifters equipped with unpumped conductivity/temperature sensors (SBE37SI or SBE47) have been recently developed. Trials both off Korea (in 2004) and in the productive northeast Atlantic region of the Bay of Biscaye (COSMOS project, 2005) have been done, which suggest that the system works most of the time and can yield fairly reliable data (*Reverdin et al., 2007*). During COSMOS, various comparisons were available which allowed drift estimation. During the first 65 days corresponding to the time of largest phytoplankton blooms, the increase in negative bias averaged -0.007. During the later summer season, the bias also increased at a comparable rate with the largest bias increase observed of -0.055 over 8 months, but also some cases with very little change were found. Mid-day values were found to be unrealistic for 10% of the days (April through September) corresponding to low wind situations.

There is also a drifter (CARIOCA) developed in 1999 with one pumped Microcat cell system (the pump at 2m depth activated once per hour) that has been regularly tested during the last 6 years. The few comparisons that are available (after up to one year at sea) suggest that the salinity drift remains weak and is less than 0.02. Development of other sensor systems, including pumped and mechanically cleaned sensors is in progress to be implemented on SVP drifters. Choice of the most appropriate cell type will depend on the area of investigation and the specific research goals. The issue that has to be carefully addressed to choose between pumped and unpumped systems is in weighing the extra-accuracy obtained with a pumped or mechanically cleaned system against increased energy consumption, weight, and cost. The estimated incremental cost is $2K-$3K to add a conductivity/temperature sensor to an SVP drifter. A reasonable investment to equip at least 25% of the total array (~300 drifters) will supply an adequate number for specific targeted study areas as part of organized process experiments and sustained satellite calibration efforts is recommended.

Gliders For all their importance to salinity monitoring, Argo floats are not ideal for investigating regions with high spatial variability, nor shallow regions. Another recently developed autonomous vehicle, the glider, can play an important role in these areas. Like profiling floats, gliders also use buoyancy changes to cycle up and down in the water column. Additionally, they move laterally while cycling by shifting their center of mass. Glider paths can be altered externally by instructions relayed through two-way satellite communications systems such as Iridium. The gliders cycle continuously as opposed to drifting like the profiling floats. Gliders have already been used extensively in the Labrador Sea (*Eriksen et al, 2001*) and as part of a monitoring program in Monterey Bay, California. The glider types presently in use, Slocum, Spray, and Seaglider, have maximum depths of 1000, 1500, and 2000 meters respectively.

The Deepglider project is presently developing a Seaglider with much deeper depth capabilities. The goal of the project is a glider that can dive to 6000 meters. To dive that deep while preserving battery power, a lightweight, durable hull material is needed. A composite carbon fiber hull has been used in three experimental Deepgliders. One prototype has now operated in the open ocean to a depth of about 2700 meters (information on Deepglider provided courtesy of C. Eriksen). This capability is important, since we've seen that changes in salinity can reach deeper than 2000 meters (*Section 2*).

Gliders can also play a key role in monitoring of freshwater signals in shallow water. The freshwater discharges of rivers and melting glaciers show up as fresh, buoyant boundary currents around the rim of the ocean that can have significant impact on transports yet be difficult to monitor by other means.

Ship deployed CTD Until Deepglider is ready for widespread deployment, the need to monitor salinity at depths greater than 2000 meters must be handled by ship deployed CTDs. Although the expense of shipboard operations prevents frequent reoccupation of CTD sections, it is important to continue to occupy them at least at decadal intervals to allow some insight into water-mass variability in the deep ocean. For instance, repeat CTD sections such as 24°N in the Atlantic have been useful in monitoring and in transport studies (*Bryden et al., 2005).* In addition, these sections provide a reference-quality *in situ* dataset for comparison to CTDs on autonomous sensors (*Wong et al.*, 2003).

7. Modeling and Assimilation

Ocean general circulation models have been used to examine the role of salinity in controlling processes such as the meridional overturning circulation since at least the 1970s (*Semtner, 1974*). Key technical issues include representation of diapycnal mixing, and application of conservation of mass. These processes are illustrated by examining the role of salinity within the mixed layer. Integrated vertically through a mixed layer of depth *h(x,y,t),* the time rate of change of salinity ([S]) is determined by a combination of surface flux, horizontal advection, subsurface processes, and mixing:

$$\frac{\partial [S]}{\partial t} = \frac{(E-P)S}{h} - \vec{v}\cdot\nabla_h S + subsurface + [MLmixing]$$
$$subsurface = \alpha\{[S]-S_{-h}\}\frac{\partial h}{\partial t} - [w\nabla_z S] + [\nabla_z (k\nabla_z S)]\Big|_{z=-h} \qquad (1$$

Here the subsurface processes include mixed layer deepening ($\alpha = 1$ if $\partial h/\partial t$ is positive and zero otherwise). The distribution of annually averaged surface flux closely resembles the freshwater flux, (**Fig. 1)**, with positive values in the subtropics and negative values in the tropics and subpolar regions. Horizontal salt advection within the mixed layer, **(Figure 11)**, can be diagnosed from a data assimilation analysis. The largest values of advection occur in the tropics dues to the presence of both strong currents and large horizontal salt gradients. In contrast, the subtropical gyres are regions of weak currents, homogeneous salinity, and thus weak salinity advection.

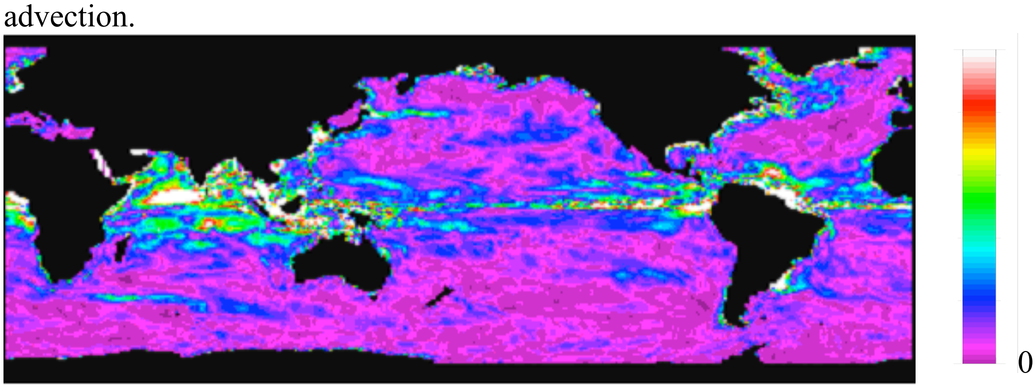


Figure 11 Time mean horizontal advection of mixed layer salinity $|(-\vec{v} \cdot \nabla S)|$. An alternative approach to determine terms in the salt budget based on constraining the state variables of temperature and salinity to match their climatological monthly averages and then using the momentum and salinity budgets to infer the flux terms (*S. Kim, personal communication, 2006*). The color range is 0-3.

Diapycnal mixing of salt across density surfaces involves a complex array of processes. Within the main thermocline these processes include internal wave breaking (*Polzin et al., 1995*) and double-diffusive processes (*Schmitt et al., 2005*). All commonly used ocean general circulation models have salinity as a state variable, rather than water mass. Thus boundary fluxes are represented by fluxes of salt rather than corresponding fluxes of freshwater. Newer numerical representations allow for either an implicit or explicit change of sea level, thus allowing for rainfall-driven barotropic circulations and other thermo- and halosteric effects (see *Griffies et al., 2001* for a summary of different numerical approaches to including a free surface).

Data assimilation uses direct observations of ocean variables to correct model simulations (*Kalnay 2002; Wunsch, 2006)*. Some applications such as the Global Ocean Data Assimilation System (*Ji et al., 1995*) are associated with seasonal forecasting projects. Others such as the Bluelink effort (*Oke et al., 2005*) are focused on a geographic region. Still others are focused on examining long-term changes in ocean climate (ocean reanalysis, see e.g. *Carton and Giese, 2007*). The basic observation set includes the historical temperature and salinity database discussed in Section 6. The machinery of data assimilation allows information about the model temperature errors as well as direct observations to correct salinity by exploiting covariances between temperature and salinity errors. While historical analyses of salinity changes are limited (in the case of the mid-depth and deep ocean severely so) due to availability of observations, two enhancements to the observing system offer the potential to revolutionize data assimilation-based salinity estimates. The first is the recently deployed Argo float array, while the second is the upcoming Aquarius satellite surface salinity mission. Assimilating salinity information into ocean models has been shown to reduce RMS errors, particularly in the tropics, of both salinity and temperature analysis fields. Continued effort is required to determine the impact of global salinity information on ocean analyses, especially on longer time scales, once the Argo array is completed and fully deployed for several years.

More sophisticated inverse modeling attempts to satisfy the tracer transport equations exactly, analogous to the ocean general circulation model. In the four dimensional variational approach of *Stammer et al. (2003)* model errors are ascribed to errors either in the initial conditions or in the surface fluxes of momentum, heat, and freshwater. For their study initial conditions are provided by climatological temperature and salinity, while surface flux is provided by the NCEP/NCAR reanalysis. Thus, inconsistencies between the ocean model and salinity observations can be resolved by correcting the imposed surface freshwater flux. Like numerical simulation, the approach offers a way of diagnosing the surface atmospheric hydrologic cycle by observing its impact on the ocean. Since the marine hydrologic cycle represents the vast majority of the global water cycle, these approaches will be essential to future monitoring of the climate system.

8. Salinity and the Variability of the Meridional Overturning Circulation

Due to its fundamental role in heat transport for the climate system of the Earth, the Atlantic meridional overturning circulation (MOC) has garnered increasing attention. The UK "Rapid Climate Change" program has focused on this for several years as have other EU and South American efforts. With a commitment to this research area within the Ocean Research Priorities Plan, we feel that increased attention to salinity measurements will make a key contribution to this effort.

Indeed, salinity is central to the whole issue of variability of the thermohaline circulation. A large body of paleoceanographic data has linked past abrupt climate changes with freshwater flooding from melting ice. Many models have been run to simulate such effects for the Younger Dryas and "8.2 kyr BP" events. The idea is that sufficient freshwater flooded the North Atlantic from the discharge of breaking ice-dams to cap-off the ocean and cease the production of dense waters normally formed at polar latitudes by atmospheric cooling. The suddenness of the the ocean response to such a capping is illustrated by ice-core records that indicate that climate changed dramatically in a decade or less during the onset of these events.

As discussed in *Section 3* coupled climate models run under an increasing-CO_2 scenario show a slowing of the MOC due to increased freshwater inputs in high latitudes due to the elevated water vapor carrying capacity of a warmer atmosphere, and increased glacial melt rates are the sources of the high latitude freshening in the models (*Alley et al, 2002*). Regional cooling around the northern North Atlantic is also often predicted, as less warm water is able to penetrate poleward. However, much remains controversial in such scenarios. There are many outstanding questions, such as:

- How much saltier are the source waters from the subtropics and to what extent do they compensate for the high latitude freshening?
- Why has the freshening been mixed to great depth instead of capping off the surface ocean?
- How can freshwater "hosing" experiments be reconciled with the actual tendency for buoyant sources to become right-turning boundary currents?
- How do the freshwater boundary currents communicate property changes into the deep ocean?
- How will freshening affect stabilities and mixing rates in the rest of the ocean, since models run with "constant energy for mixing" rather than "constant mixing rate" show an accelerated MOC rather than a slowing (*Nilsson et al, 2003*)?
- What is the critical balance between mixing rates and freshwater forcing that can tip the ocean circulation into a regime change (*Zhang et al, 1999*)?
- How do changes in wind forcing over the North Atlantic influence the strength of the MOC?
- Can monitoring of freshwater anomalies in the Atlantic contribute to decadal climate predictability?

Clearly, an improved salinity monitoring system will be crucial to any efforts to advance our understanding of the climate-relevant circulation changes of interest in the Ocean Research Priorities Plan.

9. Recommendations

There are several key motivations for improving knowledge of the role of ocean salinity variability in the global climate system:

- Ocean salinity is an important component (indicator) of "global water cycle" variability, and provides information on the flux of freshwater with the atmosphere (e.g., precipitation), with the terrestrial and crysopheric components of the global climate system, and within the ocean. Description and prediction of the global water cycle in the context of global climate change can be only be fully realized when the marine branch of the hydrological cycle is considered.

- Ocean salinity is a fundamental ocean state variable and a tracer of ocean circulation and important dynamical ocean processes that govern the uptake and redistribution of ocean heat and carbon – critical elements of the global climate system. Increasing evidence suggests ocean variability is linked to changes in extremes of the water cycle (e.g. droughts, floods) elsewhere.

- Ocean salinity likely contributes to predictability of the climate system (e.g. for ENSO and for multi-decadal variability in the Atlantic (*Griffies and Bryan, 1997*).

- Ocean salinity changes directly impact the exchange of CO_2 between ocean and atmosphere and may affect marine species and ecosystems.

The current knowledge of ocean salinity variability is hampered by lack of more than a few long-term salinity records. Available observations indicate remarkable changes of ocean salinity are underway in some regions. Unfortunately, it is unclear if these changes are attributable to natural variations, what processes may be involved, how they may or may not be consistent with changes in other components (e.g. precipitation) of the global water cycle, how long such changes have been underway, or how widespread they might be. The Argo observation network is a critical component of a global salinity observing system; however, it does not (as currently configured) sample below 2000m nor near the ocean surface. It also does not provide observations in some critical regions (e.g. the Gulf of Mexico and Caribbean, key areas for hurricane intensification).

The value of future global surface salinity measurements from space is very promising. Their value can be greatly increased if surface salinity measurements are carefully analyzed within the context of the global water cycle, especially its ocean component. In practical terms this would require integrating the in-situ and remotely-sensed components of the salinity monitoring system. Such a system should aim to provide a variety of products with specified uncertainties. Complementary products such as net freshwater flux into the ocean would also be very helpful in improving quantification of global coupled water cycle changes.

In order to fully characterize, possibly predict, and attribute changes of the global water cycle in the ocean (and exchanges between the ocean, atmosphere, and sea ice), knowledge of the many mechanisms and coupled dynamics that determine salinity must be greatly expanded. There is an unacceptable range of uncertainty of the magnitude of freshwater exchanges between the ocean and atmosphere as well as the lateral fluxes of freshwater within the ocean. Closing the coupled water budgets in select regions could be very helpful in quantifying (and hopefully narrowing) these uncertainties in the marine hydrological cycle. Planning for such ocean-based freshwater budget studies could begin now to take advantage of salinity mission validation efforts. Finally, more efforts should be undertaken to use collective knowledge on relevant processes and freshwater budget studies to analyze the fidelity of improve the depiction of processes in coupled climate models and assimilation systems.

Through its activities, the Salinity Working Group identified several key science questions that should guide existing and future research and observational efforts:

- What are our key knowledge gaps that limit the fidelity of coupled climate models in representing and predicting changes in the global water cycle and coupling to ocean circulation and climate variability?
- What are the physical mechanisms that control the Atlantic MOC and its sensitivity to interannual sea surface salinity variability, and what regions are the highest priorities for long term salinity observations?
- How does surface freshwater forcing influence ocean mixed layer dynamics in both the tropics and high latitudes and regulate heat exchange with the atmosphere, and how do these processes feed back on ocean-atmosphere coupling on intra-seasonal, seasonal and interannual time scales?
- How do varying surface fluxes of freshwater and heat generate temperature-salinity anomalies in mid-latitude waters and how are such anomalies incorporated into the central waters of the thermocline?

Priority Recommendations:
These recommendations are aimed at improving our understanding, monitoring capability and ultimately modeling and improved predictions of the global climate system.

a. Observing System Expansion
We advocate for the general expansion of salinity measurements on all ocean observing platforms. However, we here identify three near-term priorities for immediate consideration:

1. Maintain Argo Program. With so many changes being documented in regional salinity trends, and the expanding salinity data sets being provided by the Argo floats, continued analysis of temporal variability will be of great interest.
2. Surface Argo Salinity Measurements (Upper 5-m sensor). Present salinity sensors are turned off at 5 m depth to preserve calibration, it is important for AQUARIUS to obtain true surface salinity by incorporating a high resolution salinity measurement that can be corrected for drift against the deeper going sensor.
3. SSS on SVP drifters. The longevity of SSS sensors in the face of biological fouling remains a challenging issue. In order to have a significant complement of sensors on the SVP by the time of the 2010 launch of AQUARIUS it will be necessary to expand trials of various sensors and develop confidence in the technology soon.

In addition, we recommend the following future enhancements:

4. Expand Thermosalinographs on the VOS. VOS SSS data have the most impact in assimilative models when they cross regions of significant temperature and salinity variability, i.e. across water mass fronts and areas with strong mesoscale eddies (*Raicich, 2006*). A review of potential new lines and feasibility of implementation should be developed by experts in this area.
5. Maintain/Expand Moored Array Salinity Sensors. SSS sensors on moorings can be very valuable for determining the response to rainfall events, especially if deployed on flux buoys. Issues such as the sensitivity of AQUARIUS to diurnal rainfall patterns could be addressed with such data sets.
6. Repeat CTD sections. The CLIVAR Repeat Hydrography program will provide important checks of salinity trends in deep waters. However, the coverage is sparse and designed more for carbon and heat budgets than for freshwater. For example, extrema in meridional freshwater flux are found at approximately 50° and 10° North and South latitudes, yet none of these are planned for the CLIVAR Repeat Hydrography program. In particular, the 48° N Atlantic section AR19 could be considered as a freshwater flux line, particularly if complemented with gliders or moorings for monitoring the shallow fresh currents at the western boundary.
7. Glider lines. Glider technology is advancing quickly, and will be ideal for monitoring water mass and currents in a variety of oceanic regimes. The most immediate application may be in coastal boundary currents, which are generally fresher than off-shore waters and thus represent significant freshwater transports. These are accessible to present shallow water gliders. Site where they can complement an existing deep-water monitoring program are especially attractive (e.g. Line W off New England).
8. Maintain the ocean time series stations, as BATS and HOT, which can resolve seasonal and interannual fluctuations and long term trends for the entire water column.

b. Analysis

Data quality control is of paramount importance for salinity, and only properly vetted data bases should be used for such studies. The Argo and GODAE projects may be providing the needed quality control, but such efforts should be monitored and reviewed for effectiveness on a regular basis. We recommend increased international and US coordination of data management activities that consider ocean salinity data, metadata, best practices of quality flagging, and provision of salinity information and products/analyses (currently these activities are distributed amongst several programs and centers).

Also of interest for mapping the salinity field is a better understanding of the scales of variability in different oceanic regimes. Surface salinity generally has shorter scales of variability than surface temperature, because it lacks any direct feedback on atmospheric fluxes, which tend to smooth lateral variations in SST. Some tropical regions have very abrupt, short scales of variability in salinity, while subtropical gyre regions appear to have a high correlation between salinity and temperature changes in a density compensating manner (*Rudnick and Ferrari, 1999*). Such correlations may allow the use of SST maps to identify salinity fronts. In all regions it would be helpful for mapping purposes to develop statistics on correlations scales, and analysis of the existing thermosalinograph data sets for these should be encouraged.

c. Model Improvements
Great progress has been made in the last decade in understanding how the interior ocean mixes through the use of tracer release experiments. Dramatic spatial variability in diapycnal mixing rates is now known to be common. Such variations impose a much richer baroclinic flow structure on the ocean than the uniform interior mixing assumed in most models. However, such variations in mixing rate are still largely missing from models. Upper ocean mixing and its interaction with Ekman advection and outcropping isopycnals is a particularly challenging problem and one closely related to the use of SSS data to constrain net water fluxes between ocean and atmosphere. We must also recognize that heat and salt do not mix at the same rates due to the action of double diffusive mixing. The CLIVAR Climate Process Teams (CPTs – see www.usclivar.org/science.html#model) may be helpful in this regard but much greater resources are required to expand the number of teams and to bring a substantial observational component to the efforts.

d. Quantitative water flux and process experiments
With significant progress apparent in the use of autonomous floats and gliders for the measurement of water properties and velocities, it is now feasible to consider a dedicated effort to constrain estimates of air-sea interaction (e.g., E-P) with a "CAGE" type budget experiment for the ocean (**Figure 12**). That is, with reasonable densities of surface drifters, moorings and profiling floats in the interior of a control volume, and gliders monitoring the boundaries, coupled with satellite measurements of winds, sea surface height and salinity from Aquarius SAC/D , it should be feasible to construct budgets for heat and freshwater for an upper ocean parcel. Upper ocean mixing processes must also be measured.

Two types of ocean regimes are preferred for such an experiment. The first could be a simpler mid-gyre evaporation regime, where the subtropical salinity maxima are formed. The second could be in a tropical high precipitation regime.

1. *Evaporation Regime.* At the salinity maximum, horizontal salinity gradients vanish, so advection is of small importance in the surface layer. Generally these areas have weak eddy fields, making the sampling problems less severe. Similarly, precipitation is usually relatively weak, meaning less surface salinity variance, thus increasing the signal to noise ratio. With net surface evaporation and Ekman convergence, vertical mixing and subduction processes are of prime importance.

2. *Precipitation Regime.* The strongest precipitation regimes are in the tropics, and tend to have strong zonal advection associated with them. This advection, stronger eddy fields and patchiness of fresh anomalies pose a greater sampling challenge, so this is suggested as an alternate or second experiment. The physics of barrier layers would be of interest. Calibration and validation of remote sensing techniques for precipitation, as well as the utility of salinity measurements for constraining air-sea fluxes would also be of particular interest.

In developing plans for such experiments it will be important to identify high signal/noise areas, where the effort can provide the greatest benefit in constraining estimates of surface forcing.

Also, it would be useful to identify the regions of greatest disagreement between surface flux climatologies. In refining experimental plans, observing system simulation experiments should be carried out to optimize deployment of resources.

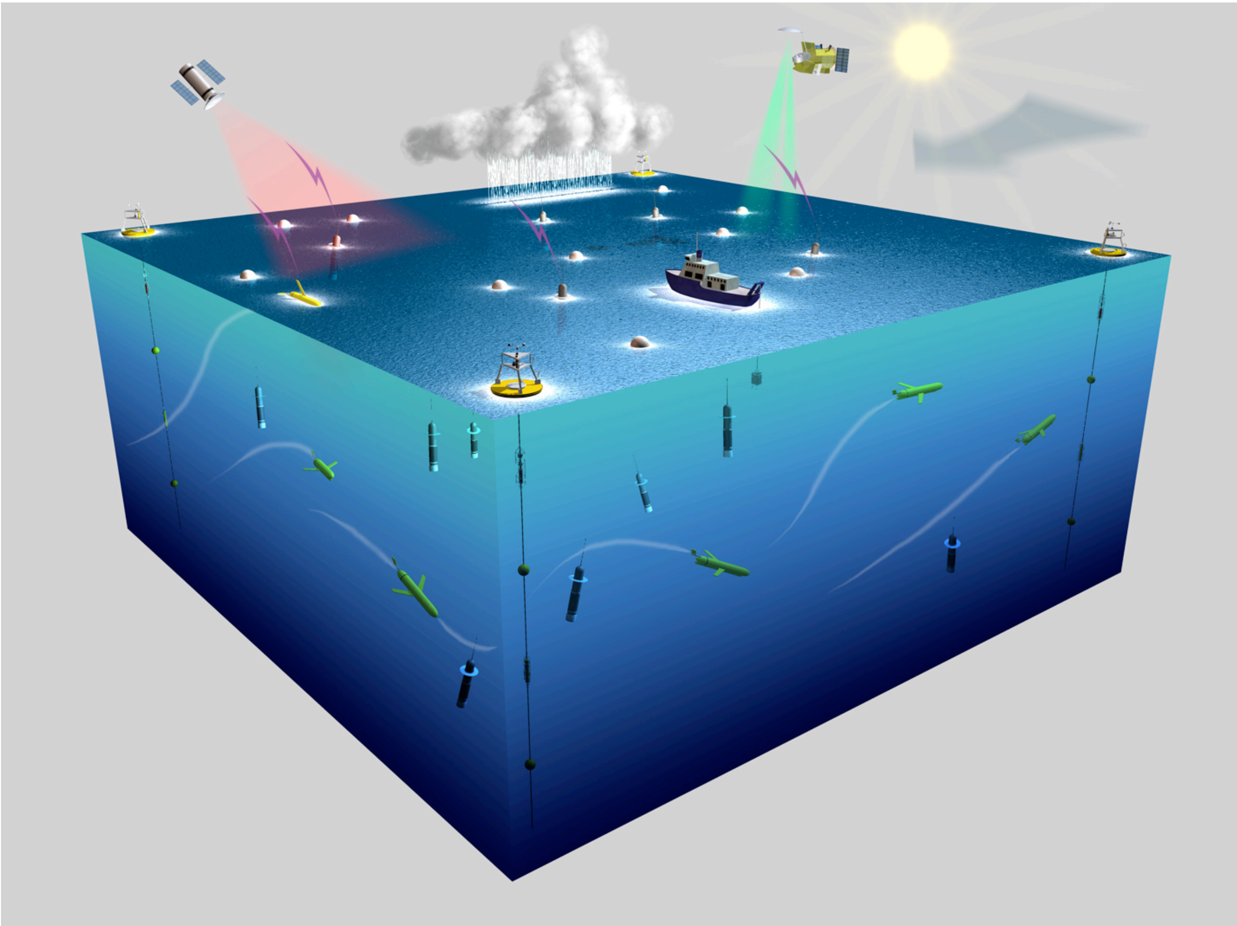


Figure 12. Schematic showing floats, drifters, gliders, moorings, ships and satellites sampling a volume of ocean in sufficient density to constrain the upper ocean salinity budget and thus the surface freshwater flux. Gliders patrol the boundaries, floats and drifters monitor the interior and flux buoys and satellites assess air-sea interactions.

e. Enabling Mechanisms

The emergence of new observing tools and capabilities along with improving models and ocean analyses holds great promise to bring about significant leaps in monitoring, understanding, and modeling the large marine branch of the global freshwater cycle, which in turn will help in addressing the key science questions presented in this report. However, the Working Group on Salinity was not charged to continue beyond developing this report. Consequently, there is no one single group to carry the recommendations of the Working Group forward, or to identify, encourage, and catalyze needed activities; however, there are several groups that should be engaged to address the challenges and recommendations described in this report. These groups include, Argo, OOPC, JCOMM, CLIVAR

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U.S. CLIVAR Salinity Workshop
8-10 May 2006
Woods Hole Oceanographic Institution

1.1.1.

8 May (Day 1)		
0730	Continental Breakfast	
0830 - 0845	Welcome and Introductions, goals and logistics	Carton/Schmitt
	Session 1: Surface Water Fluxes	
0845 - 0915	New estimates of global evaporation	Yu
0915 - 0945	Estimates of global precipitation	Arkin
1015 - 1030	**Morning Break**	
1030 - 1100	Evaporation minus Precipitation	Schmitt
1100 - 1200	**Discussion:** Future of surface flux estimates: can oceanic data provide constraints?	Schmitt
1200 – 1300	**Break for Lunch**	
	Session 2: Salinity structure: trends and variability	
1300 - 1330	Salinity and Climate Dynamics	Johnson
1330 - 1400	Atlantic Ocean Salinity Trends	Dickson
1400 - 1430	Salinity trends from archival data	Curry
1430 - 1500	Arctic Ocean Salinity Trends	Proshutinsky
1500 - 1530	**Afternoon Break**	
1530 - 1630	**Discussion:**	
1730 - 1830	**Poster Session and light snacks/beverages**	
9 May (Day 2)		
0730	Continental Breakfast	
	Session 3: Trends and Variability of Salinity	
0830 - 0900	Southern Ocean Salinity Trends	Gordon
0900 - 0930	Pacific Salinity Variability	Lukas
0930 -	Tropical Salinity Variability	Delcroix

1000		
1000 - 1015	**Morning Break**	
1015 - 1115	**Discussion:** What do changing salinities tell us about the water cycle?	Large
	Session 3: Salinity and Climate	
1115 - 1145	Salinity and El Nino predictability	Busalacchi
1145 - 1215	Paleo-salinity issues	M. Schmidt
1215 - 1315	**Lunch**	
	Session 4: Observations and monitoring opportunities	
1315 - 1345	Salinity Trends revealed by ARGO	Riser
1345 - 1415	Thermosalinographs on VOS	Reverdin
1415 - 1445	Inferring fluxes from surface convergences: salinity on surface drifters	Niiler
1445 - 1500	**Afternoon Break**	
1500 - 1530	In-situ sensors: new developments	Schmitt
1530 - 1700	**Discussion:** Are there specific experiments that need to be done? What are the observational requirements for monitoring salinity variability in the coastal zone, the tropics, subtropics, and at high latitudes?	Gordon
10 May (Day 3)		
0730	Continental Breakfast	
	Session 5: Future Prospects	
0830 - 0900	Remote Sensing and Aquarius Mission Overview	Lagerloef
0900 - 0930	Improved salinity measurements to constrain oceanic fluxes: Prospects for data assimilation	Carton/Large
0930 - 1030	**Discussion:** What are the elements of an improved salinity monitoring system for climate? water cycle? Aquarius	Schmitt
1030 - 1045	**Morning Break**	
1045 - 1200	**Discussion:** SWG White paper and future plans	
1200	**Adjourn**	

1.1.2. Salinity Posters Presentations:

- Distribution of mixed layer properties in North Pacific water mass formation areas: comparison of ARGO floats and World Ocean Atlas 2001 - *Frederick M. Bingham*

- Using Sea Surface Salinity as a parameter in the Gravest Empirical Mode - *Deirdre A. Byrne*
- The Freshening of Surface Waters in High Latitudes: Effects on the Thermohaline and Wind-driven Circulations - *Alexey Fedorov*
- The SMOS approach to retrieve sea surface salinity from L-BAND radiometric measurements - *Jordi Font*
- Low Frequency Variation of Sea Surface Salinity in the Tropical Atlantic - *Semon Grodsky*
- Role of assimilation of salinity data in tropical Pacific Ocean simulations - *Eric Hackert*
- Upper ocean T-S variations in the Greenland Sea and their association to climatic conditions - *Sirpa Hakkinen*
- How was Seasonal Variability of Upper Ocean Salinity Simulated by Global Ocean Data Assimilation Systems? - *Boyin Huang*
- Using Data Mining Technique to Discover Useful Salinity/Temperature Patterns in ARGO data - *Yo-Ping Huang*
- Variability Scales of Sea Surface Salinity - *S. Daniel Jacob*
- Internnual Variations of mixed layer Salinity inthe Equatorial Pacific Ocean - *Seung-Bum Kim and Frank J. Wentz*
- Poleward propagation of compensated salinity anomalies in the North Atlantic Ocean and impacts at high latitudes - *Audine Laurian*
- Upper Ocean State and Variability in the Subpolar North Atlantic from Lagrangian Floats - *Xingwen Li*
- Internal Variability of sea surface salinity in the tropics - *Raghu Murtugudde*
- Modeled and observed Atlantic salinity changes over the last half-century - *Anne Pardaens*
- Decadal Changes of Pacific Salinity - *Li Ren*
- Ocean surface salinity in the tropical oceans using satellite derived OLR - *Bulusu Subrahmanyam*
- Impact of ARGO salinity observations on ocean analysis - *Chaojiao Sun*
- The role of salinity in the climate response to an intensified water cycle - *Paul Williams*
- Understanding and Attributing Subpolar North Atlantic Freshening - *Peili Wu, Michael Vellinga and Richard Wood*
- Observational evidence of winter spice formation - *Stephen Yeager*
- How does the subsurface salinity maximum in the South China Sea reach its equilibrium - *Zuojun Yu*
- An Empirical Parameterization for the Salinity of Subsurface Water - *Rong-Hua Zhang*

Aquarius Agenda

10 May (Day 1)		
1300-1315	Welcome and Introductions, goals and logistics	G. Lagerloef / R. Schmitt
	Session 1: Aquarius/SAC-D Mission and Project Overview	
1315-1330	NASA Ocean Program and Ocean Salinity Science Team plans	E. Lindstrom
1330-	Aquarius/SAC-D Overview and Mission Status	G. Lagerloef

1350		
1350-1410	SAC-D Observatory and SAC-D Instruments	R. Colomb
1410-1430	SMOS Overview and Mission Status	J. Font
1430-1450	Aquarius/SAC-D Education and Outreach Program	A. deCharon
1450-1510	**Afternoon Break**	
1510-1530	Mission design (orbit, sampling, requirements, data products and distribution... etc)	G. Lagerloef
1530-1600	Salinity Retrieval Algorithm Geophysical Corrections and Simulator	D. LeVine
1600-1630	Instrument System and Backscatter Correction	S. Yuch
1630-1700	Error Analysis and Calibration / Validation Approach	G. Lagerloef
1700-1730	**Discussion and Questions**	Moderator: E. Lindstrom
1730 - 1930	**Conference Dinner - Clambake**	
11 May (Day 2)		
0730	Continental Breakfast	
	Session 2: Remote Sensing	
0830 - 0850	Simulation of Aquarius Salinity Retrievals	F. Wentz
0850 - 0910	Land contamination of the Aquarius signal over ocean induced by the antenna gain patterns	E. Dinnat
0910 - 0930	Observing regional salinity signals of major rivers: Exploring Aquarius and SMOS resolution limits	Burrage etal.
0930 - 0950	Sky Glitter Corrections in SMOS Salinity data Processing	J. Tenerelli
0950 - 1020	**Morning Break**	
1020 - 1050	**Discussion:** Science impact and mitigation of land contamination and other errors	Moderator: D. LeVine
1100 - 1200	**WHOI Seminar:** *Large Scale Heat and Freshwater Budgets of the Arctic*	M. Serreze, U. of Colorado
1215 - 1320	**Lunch Break - Poster Session** (see below)	
	Session 4: Trends, Water Masses, Circulation and Water Balance	
1320 - 1340	The Freshening of Surface Waters in High Latitudes: Effects on the Thermohaline and Wind-driven Circulations	A. Federov
1340 -	Upper ocean T-S variations in the Greenland Sea and their association	S. Hakkinen

1400	to climatic conditions	
1400 - 1420	Observations Evidence of Winter Spice Formation	S. Yeager and B. Large
1420 - 1440	Decadal Changes of Pacific Salinity	L. Ren and S. Riser
1440 - 1510	Distributions of mixed layer properties in North Pacific water mass formation areas: comparison of ARGO floats and World Ocean Atlas 2001	F. Bingham
1510 - 1530	**Afternoon Break**	
	Session 4: Continued	
1530 - 1550	Water Balance over the Tropical and Subtropical Oceans	T. Liu
1550 - 1610	Using Sea Surface Salinity as a parameter in the Gravest Empirical Mode	D. Byrne
1610 - 1630	Low Frequency Variation of Sea Surface Salinity in the Tropical Atlantic	S. Grodsky
1630 - 1700	**Discussion: Science issues and satellite data applications**	Moderator: A. Gordon
12 May (Day 3)		
0730	Continental Breakfast	
	Session 5: Tropical Dynamics, modeling and Assimilation	
0830 - 0850	An Intermediate Model for Sea Surface Salinity Variability and Predictability in the Tropical Pacific Ocean	R. Zhang
0850 - 0910	How do rains and winds change the SS in the Indian Ocean which feedbacks onto the atmosphere?	C. Perigaud, Y. Chao
0910 - 0930	Kuroshio paths at the Luzon Strait revealed by satellite images and confirmed by a regional ocean model	Z. Yu
0930 - 0950	Interannual Variations of Mixed-Layer Salinity of the Eastern Equatorial Pacific Analyzed Based on the Budget Closure	S. Kim
0950 - 1010	**Morning Break**	
1010 - 1040	Sensitivity of Sea Surface Salinity and Freshwater Transports to Surface Forcing Conditions	D. Jacob
1040 - 1100	Impact of ARGO Salinity Observations on Ocean Analysis	C. Sun
1100 - 1130	**Discussion:** Science issues and satellite data applications	Moderator: Y. Chao
1140 - 1230	**Wrap-up discussions, conclusions and recommendations**	Moderator: G. Lagerloef
1230	**Workshop Adjourn**	

1.1.3. Aquarius Poster Presentations

- Education & Public Outreach for the NASA Aquarius Mission - *A.deCharon*
- Centers for Ocean Sciences Education Excellence (COSEE) - Ocean Systems - *A.deCharon, etal*
- Ocean Science Education and Outreach: Identifying and Meeting Scientists' Needs - *A.Thorrold*
- Thermosalinograph (TSG) transects maintained by NOAA/AOML - *G.Goni*
- Temporal and Spatial Salinity variations in the GIN Sea - *S.Dransfeld, J.Font*
- Ocean Surface Salinity in tropical Indian Ocean using satellite derived OLR - *S.Bulusu*
- Retrieving SSS in Coastal Areas from SMOS data - *S. Zine*
- Internal Variability of sea surface salinity in the tropics - *R. Murtugudde*

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