# Salinity Processes in the Upper-Ocean Regional Study (SPURS)

SPURS Workshop Report Committee[1]

January 2010

## I. Introduction

As articulated in the report of the US CLIVAR Salinity Working Group (2008), no part of the climate system is as important to society as the global hydrological cycle; yet we lack key understanding of its major element, the ocean. The ocean is the source of nearly all terrestrial precipitation, and the ocean itself is the recipient of most precipitation. Significant shifts in rainfall patterns associated with climate change will likely cause disruptions in agriculture and freshwater supplies for civilization. Ocean general circulation models used to examine such changes often require artificial salinity restoring terms to maintain stable solutions. Thus, it is of great importance to improve our abilities to monitor, understand, and model the water cycle over the oceans (See March, 2008 issue of *Oceanography* magazine; the table of contents is appended to the reference list). As upper ocean salinity (UOS) is an important variable that indicates the intensity of water exchange between ocean and atmosphere and has direct impact on the ocean's mass distribution, mixing rates, and associated interior circulation, improved observation systems for salinity and better understanding of the processes that control it are needed for progress in understanding the oceanic water cycle. In this document we propose a suite of field activities designed to improve our understanding of the physical mechanisms controlling upper ocean salinity. The planned work coincides with the US-Argentine Aquarius/SAC-D and European SMOS surface salinity satellite missions (planned for launch in 2010 and 2009 respectively) as well as the continuing, global array of ARGO profiling floats, all of which provide excellent new tools to monitor ocean salinity.

## II. Sea Surface Salinity (SSS)

The measurement of UOS has long posed significant technical challenges (e.g. Wong et al., 2003). Additionally, the characteristic short spatial scale of UOS makes individual measurements obtained from *in situ* platforms problematic in describing the texture of the larger scale patterns. In many areas, the UOS salinity balance has not been well understood. It can be influenced by horizontal advection, air-sea exchange of freshwater, and vertical mixing and entrainment among other processes. In spite of these difficulties, with present and soon-to-be available technology it will shortly be feasible to carry out field efforts to assess the upper-ocean salinity/freshwater budgets. With significant progress apparent in the use of autonomous floats and gliders for the measurement of water properties and velocities, it is timely to consider a dedicated effort to quantify the processes governing the UOS and constrain estimates of air-sea interaction (e.g., $E-P$), within a near-surface ocean volume, in an updated version of the "CAGE" concept as proposed Bretherton et al. (1982) (**Figure 1**). That is, with reasonable sampling densities of surface drifters, moorings, gliders, ship-based hydrography and profiling

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floats deployed in an oceanic control volume, coupled with measurements of winds, sea surface height and salinity from satellites, and *in situ* estimates of small-scale ocean mixing, it will be possible to construct budgets for heat and freshwater for a bounded region of the upper ocean within acceptable uncertainties.

The evolution of UOS, $\langle S \rangle$, on synoptic and longer timescales in an outcropping layer of thickness $h$ can be written as:

$$\underbrace{h\frac{\partial \langle S\rangle}{\partial t}}_{a} = \underbrace{-h\langle \vec{u}\rangle \bullet \nabla \langle S\rangle}_{b} - \underbrace{\nabla \bullet \int_{-h}^{0} \hat{\vec{u}}\hat{S}dz}_{c} - \underbrace{\left(\langle S\rangle - S_{-h}\right)\left(\frac{\partial h}{\partial t} + \vec{u}_{-h} \bullet \nabla h + w_{-h}\right)}_{d} + \underbrace{\left(E-P\right)S_0}_{e} + \underbrace{SSM}_{f} \qquad (1)$$

where $\langle\ \rangle = \frac{1}{h}\int_{-h}^{0}(\ )dz$, $\hat{(\ )}$ is the departure from the vertical average, and $[\ ]_{-h}$ is the value of a property at the base of the layer. Term (*a*) in equation (1) is the salt storage, term (*b*) is the advection by the vertically averaged flow, term (*c*) is advection by the vertically sheared flow, term (*d*) includes entrainment/detrainment and subduction/obduction through the base of the layer, term (*e*) is the surface forcing from evaporation, *E*, and precipitation, *P*, and term (*f*) represents mixing by small scale turbulence (internal gravity waves, microstructure, etc) at the base of the layer. In order to assess the instantaneous evolution of salinity in a near surface regime, each of these terms would have to be evaluated from observations, an essentially impossible proposition. We choose instead to examine the evolution of UOS in regions where a few of these terms are expected to dominate, or over control volumes specifically chosen to minimize certain terms, in order to simplify the task. For example, by choosing a quasi-material surface such as an isopycnal as the lower boundary of the layer, the entrainment/subduction term (*d*) will be minimized (Moisan and Niiler, 1998). Alternatively, by evaluating (1) integrated over a control volume bounded by a surface of uniform salinity, we can potentially reduce the difficulty in calculating flux divergence terms (*b*) and (*c*) (Niiler and Stevenson, 1982; Toole et al, 2004). In developing plans for such experiments, it will be important to identify those high signal/noise ratio areas, where the effort can provide the greatest benefit in constraining estimates of surface forcing. Additionally, it will be useful to identify the regions of greatest disagreement between surface flux climatologies.

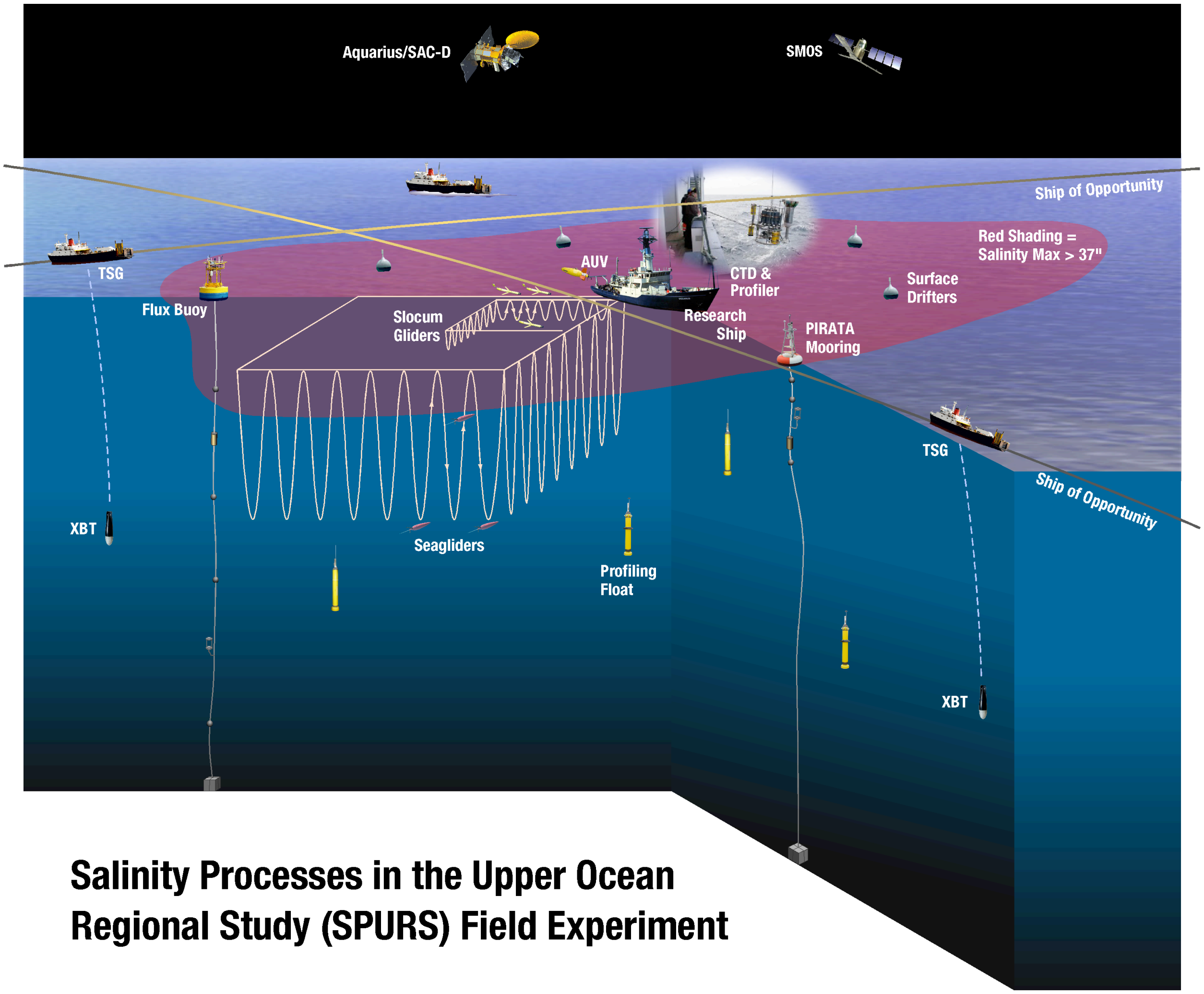


***Figure 1.*** *A schematic drawing of an experiment to examine the processes affecting the upper layer salinity of the ocean within a mid-ocean environment.*

Examination of time-mean sea surface salinity constructed with archived hydrographic data (**Figure 2**) highlights two types of ocean regimes that are suitable for evaluation of components shown in Eq 1.

1. The first is near the center of an oceanic subtropical gyre, where net evaporation leads to the formation of a horizontal salinity maximum. These regions exist at subtropical latitudes in all the world's oceans and are seemingly formed by a combination of excess evaporation over precipitation, poleward Ekman (i.e., ageostrophic) advection, subduction and horizontal eddy flux. Just equatorward of these regions are areas of maximum E-P, the process that contributes most importantly to the formation of the salinity maximum. At the center of the sea surface salinity maximum, the climatological mean horizontal salinity gradients are weak, so mean advection (the time mean or low-frequency components of terms *b* and *c* in eq 1) may be of minor importance in the near-surface layer; the velocities and salinity in the salinity equation still, however, have eddy components and related horizontal and vertical fluxes that likely will not vanish, although generally the high salinity areas have weak geostrophic circulation and weak eddy fields. An examination of non-seasonal variability of sea level in the subtropical Atlantic, for example, shows RMS eddy variability that is less than 3 cm. Similarly, precipitation

is relatively weak (term *e* is dominated by evaporation), meaning less surface salinity variance, thus increasing the signal to noise ratio. The seasonal fluctuations of the mixed layer depth, while substantial, have relatively weak horizontal gradients in this region, so the lateral induction component of term *d* should be relatively weak. Again, however, there may be an eddy contribution to this process (Gebbie, 2007). Thus, net surface evaporation, Ekman convergence, vertical mixing, and subduction processes are likely of prime importance (the ageostrophic component of term *b*, the components of term *d* associated with time variation or vertical velocity, and term *e*) in such regions. These are the regions where air-sea fluxes induce the salinity maxima of the world oceans and "end-point" contributors to the production of salinity variance. They are also sources for the high salinity shallow thermocline water that invades the tropical oceans and thus play a role in the stratification of the tropics. A comprehensive review of the processes of subduction, Ekman pumping, and surface fluxes for each of these mid-latitude evaporation regimes has been provided by O'Conner et al. (2002 and 2005).

2. The second candidate for an experiment site is in a low-latitude, high precipitation regime. The strongest precipitation regimes occur in the ITCZ near the Equator and are associated with strong zonal advection. However, the presence of advection, stronger transient variability, and patchiness of the salinity field associated with fresh anomalies generated from tropical rain cells pose a serious sampling challenge. In the western tropical Atlantic horizontal salt flux convergence related to the large Amazon discharge plays an important role (*Hellweger and Gordon 2002; Foltz et al., 2004*). Some of these difficulties might be ameliorated by going to a low-advection, high precipitation regime such as the Bay of Bengal or the Gulf of Guinea, but these choices introduce logistical difficulties with their own complexities. There are compelling aspects of the second regime, such as the role of barrier layers in controlling vertical exchange, yet the added difficulties suggest that the first candidate salinity maximum regions should be of higher priority, with this second candidate suggested as a later experiment (SPURS come in pairs).

## III. The Subtropical Salinity Maximum

O'Conner et al. (2005) have shown that there are similarities in the relatively saline UOS subtropical regions in all the major ocean basins and have suggested that such regimes play an important role in the shallow, low-latitude meridional overturning circulation. These, in turn, are critical in setting the stratification near the Equator and hence can influence the character of tropical variability. Here we review some of the major characteristics of these regions.

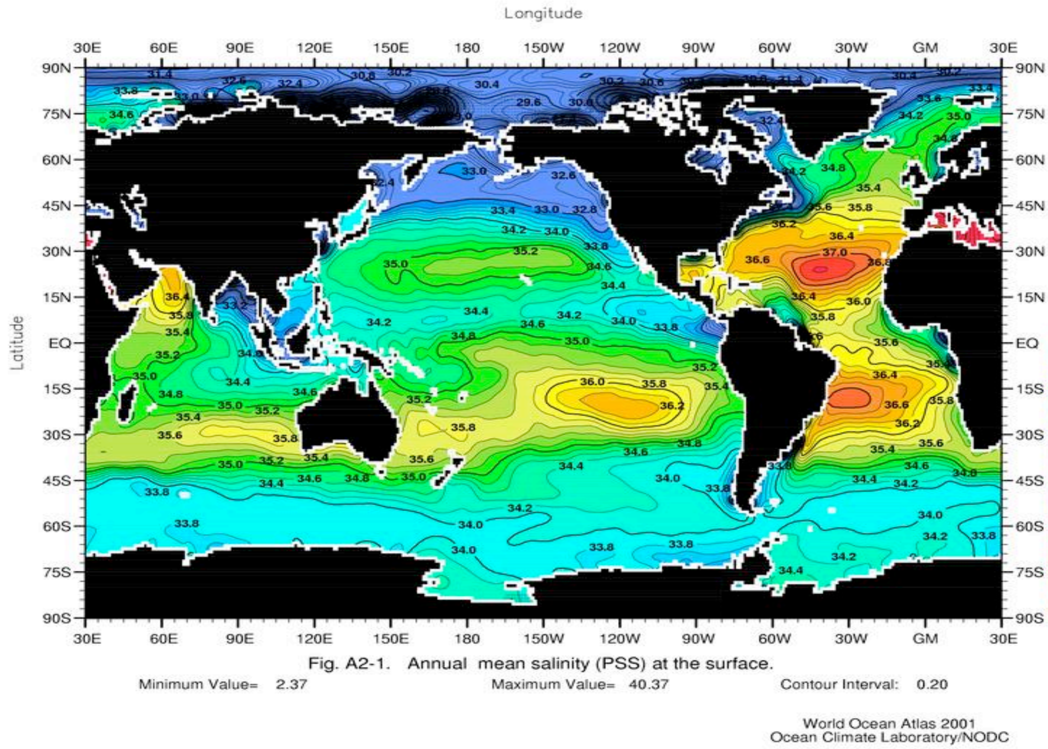


***Figure 2.*** *Time-mean surface salinity.*

The subtropical gyres of the ocean are characterized by anticyclonic circulation with swift western boundary currents and slower, equatorially- bounded return flows in the interior. Within the central "hubs" of these regimes, the localized influence of evaporation under the trade winds, acting in concert with the convergent Ekman transports, dominates the upper ocean stratification and circulation (**Figure 3**). Within these hubs, climatological mean surface salinity gradients are weak, thus reducing the importance of transport convergence by the gyre-scale circulation. Additionally, the dilution effect of coastal river discharge is zero.

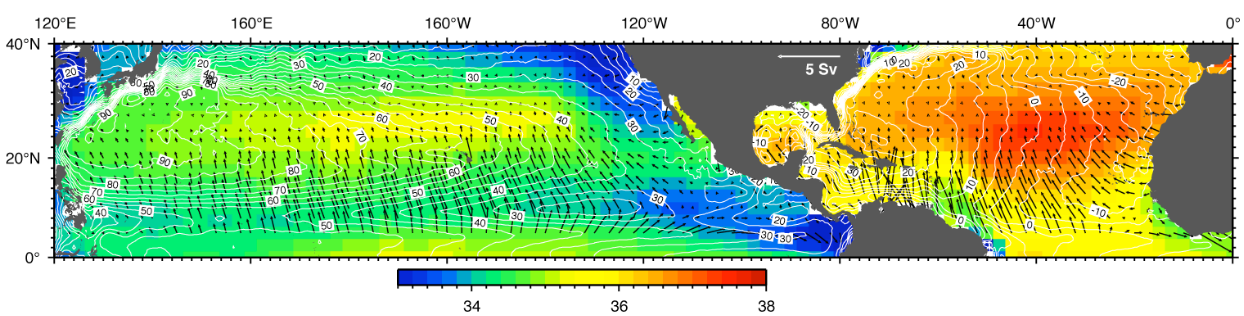


***Figure 3a.*** *Ekman transport vectors in Sverdrups (1 Sv = $10^6$ $m^3s^{-1}$) and 10 cm contours of mean dynamic topography of the sea surface. In color, the long-term mean sea surface salinity (defined as the upper 20 m salinity average). Ekman transports were computed across 2.5ºx2.5º latitude-longitude cells using long-term mean wind stresses based on ECMWF ERA-40 monthly data (Uppala et al. 2005). Sea surface salinity was computed from the 1ºx1º World Ocean Atlas 2005 (Antonov et al. 2006). Nikolai Maximenko and Peter Niiler provided the 1990-2002 mean ocean dynamic topography data (Maximenko and Niiler, 2005).*

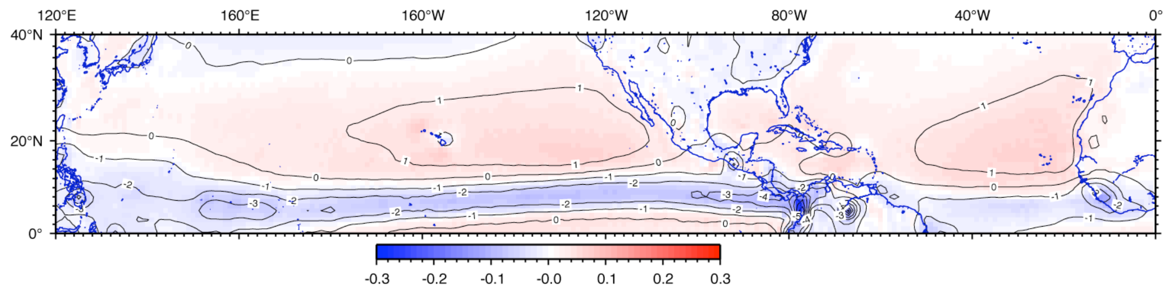


***Figure 3b.*** *Long-term average (1958-2001) of the vertical integral of the divergence of moisture flux (color; units= kg m$^{-2}$ s$^{-1}$ x 1000) computed from monthly ECMWF ERA-40 data. Evaporation minus precipitation (contours; units in m yr$^{-1}$) estimated from ERA-40 monthly surface large-scale and convective precipitation and evaporation data. If the time rate of change of precipitable water is assumed to be zero, then the vertically integrated water vapor flux divergence, can be used to estimate source (E >P) and sink (E <P) regions of atmospheric moisture.*

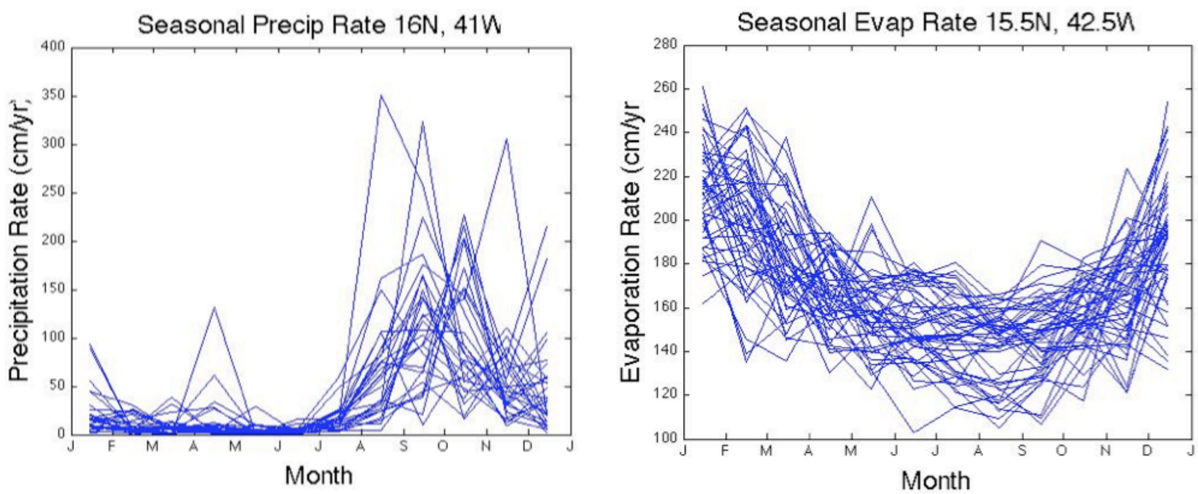


***Figure 3c***. *Seasonal variability of the precipitation (16°N, 41°W; left panel) and evaporation (15.5°N, 42.5°W; right panel) within the North Atlantic subtropical gyre. Precipitation rate plotted seasonally. Data were taken from the Global Precipitation Climatology Project (GPCP; [http://precip.gsfc.nasa.gov/)](http://precip.gsfc.nasa.gov/) monthly merged precipitation analysis (Huffman et al., 1997; Adler et al., 2003) on a 2.5° X 2.5° grid. Separate lines indicate different years, 1979-present. Only one grid point, near 16°N, 41°W, is shown for clarity, but is representative of the seasonal cycle of precipitation throughout the region 30-50°W, 15-25°N. Evaporation rate plotted seasonally (right panel). Data were taken from the OAFlux dataset of Yu et al. (2008; see also [http://oaflux.whoi.edu/)](http://oaflux.whoi.edu/). Data are monthly estimates of evaporation on a 1° X 1° grid. Separate lines indicate different years, 1958-2006. Only one grid point, near 16°N, 42°W, is shown for clarity, but is representative of the seasonal cycle of evaporation throughout the region 30-50°W, 15-25°N.*

The annual excess of evaporation over precipitation, in excess of 1 m/yr at its maximum, acts to increase UOS within the subtropical ocean. Seasonality in the value of *E-P* is evident (**Figure 3c**); note that from August through November decreased *E* and elevated *P* result in the two rates having similar values. The equatorial displacement of the evaporative maximum (**Figure 3b)** from the surface salinity maximum (**Figure 3a**) makes clear that horizontal transport must also play a role. Ekman transport, driven by the trades and westerlies, restores the salt balance by introducing lower salinity surface water from adjacent latitude belts into the subtropical hub. This Ekman mass transport drives convergence and downwelling of the salty subtropical surface water, which spreads towards the tropics as a salinity maximum layer near 150 m. In this manner the regional or localized subtropical sea-air forcing establishes a shallow meridional overturning circulation (ShallMOC), in what may be considered the oceanic equivalent of the atmospheric Hadley Cell, stretching from the evaporative, convergent subtropical regime to the wetter, divergent tropics. As the surface layer is warmed in the tropics, the shallow meridional overturning circulation represents one aspect of the poleward transport of heat and freshwater within the latitude band equatorward of ~30° in both hemispheres, a region encompassing half of the area on the globe and where the oceans carry the largest portion of the planetary heat transport. Along the western boundary, the southward Sverdrup volume transport of the interior tropical and subtropical water is balanced by poleward volume transport, which, in addition, compensates the equatorial Ekman transport induced by the westerlies north of the subtropical convergence. The Sverdrup circulation also carries the subducted salinity maximum equatorward, revealing the oceanic water cycle that complements the trade wind/ITCZ water cycle of the Hadley cell in the atmosphere.

Reverdin et al. (2007) find that seasonal anomalies in sea surface salinity have spatial scales of typically 500–1000 km and display a 1–2 month lag to freshwater flux anomalies at the air–sea interface and to the horizontal Ekman advection. They suggest that in the north-east Atlantic the late-boreal spring/summer season is less active than the boreal winter/early-spring season in forcing the seasonal SSS variability. In the north-eastern mid-latitude Atlantic, SSS is positively correlated with SST, with SSS slightly lagging SST. There is little regional temporal signal in UOS in this region, with spatial variability dominated by mesoscale noise superimposed on a mean spatial gradient, though there is some indication of a secular increase in UOS on the order of 10^-4 pss/yr (Boyer et al, 2005). An apparent decreasing trend since 2000 is probably an artifact of the fact that the later data area mainly collected from floats while the earlier are from research vessels and volunteer observing ships (Figs. 4 and 5).

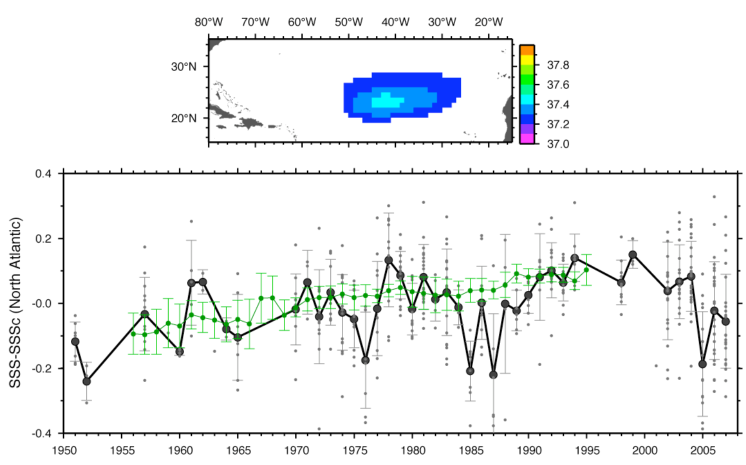

***Figure 4.*** *Annual mean sea surface salinity (upper 20 m) for the central region of the North Atlantic subtropical gyre and time series of the sea surface salinity anomaly. Data extracted from the World Ocean Database 2005 (Boyer et al., 2006). Dark circles represent the yearly average of the data; vertical lines represent one standard deviation. The small gray circles represent the individual yearly values for each box. In green, salinity pentad anomalies for the same region (Boyer et al., 2005) and its standard deviation, from 1955-59 to 1994-1998, using levels 1 to 3, corresponding to 0 to 20 m.*

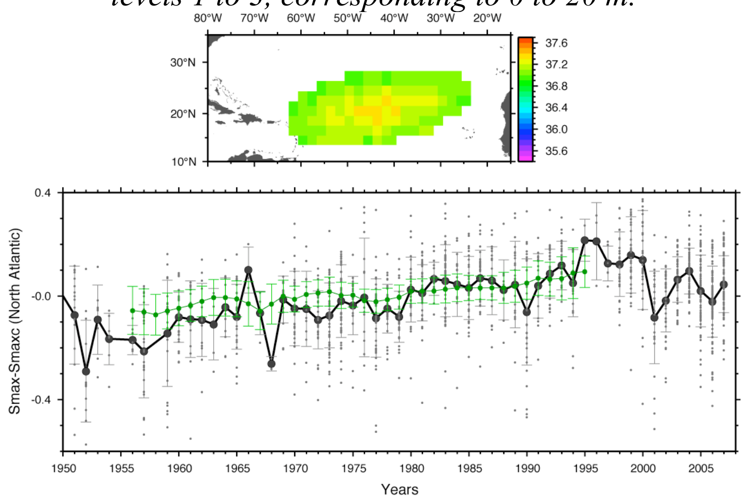


***Figure 5.*** *As in Figure 4, but for the North Atlantic Salinity Maximum (S-max). We define the S-max as the salinity maximum between 100-200 m of the water column.*

An interesting time series of near surface salinity is available from the PIRATA mooring located at 20°N, 38°W, on the southern edge of the region of the surface salinity maximum. This location is within the zone of the northeasterly trade winds which fluctuate on weekly timescales. Deployed in May, 2007, a striking feature of the mooring time series is the presence of a substantial 0.5psu freshening in the upper 80 meters beginning in late-2008. This freshening seems not to be the result of changes in local winds or freshwater flux, and thus its cause and its effect on the ShallMOC remains a puzzle.

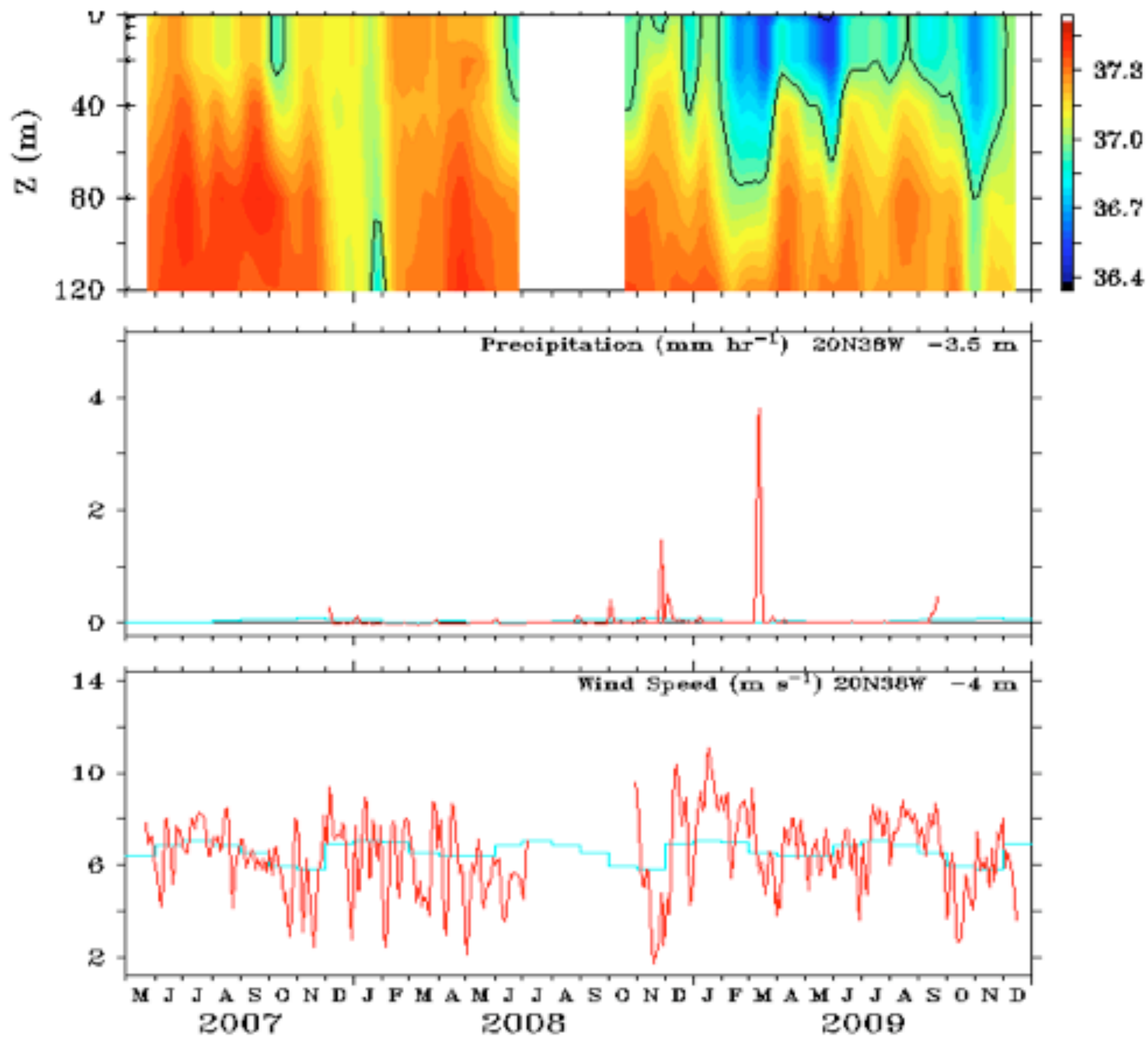


***Figure 6.*** *Time series of ocean and atmospheric variables from the PIRATA mooring at 20$^o$N, 38$^o$W. Upper panel shows monthly averaged salinity, middle and lower panels show precipitation (mm hr$^{-1}$) and wind speed (ms$^{-1}$) in red with climatological seasonal estimates in blue. Note the distinct freshening beginning in late-2008. Images are from the PIRATA website (www.pmel.noaa.gov).*

We can make a preliminary assessment of the scales of variability and balance of terms in the near surface salinity distribution by examining solutions from high-resolution general circulation models. A recent integration of the POP model (Maltrud et al, 2009), driven by a repeating annual cycle of surface forcing (Large and Yeager, 2004) provides one example. The climatological surface salinity in the middle of the winter mixed layer and the associated velocity field are shown in Figure 7a. The mean flow has a typical magnitude of 1-5 cm/s at this depth (below the Ekman layer), generally directed from northeast to southwest. In contrast, the (nearly) instantaneous flow and salinity distribution are dominated by mesoscale features (Figure 7b).

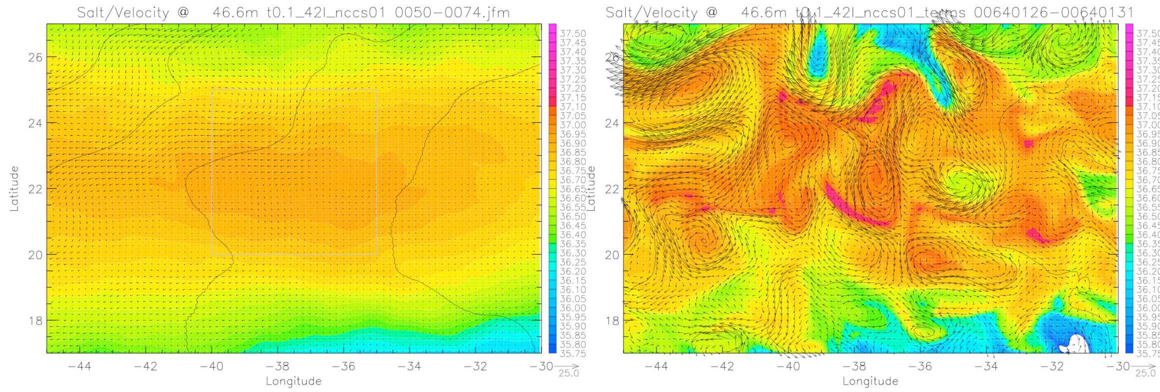


***Figure 7 (a)*** *Climatological (25 year) winter (January-March) mean salinity (color) and horizontal velocity (vectors) at 46m in the vicinity of the North Atlantic surface salinity maximum. Sea surface height is shown as black contours with a 5cm interval.* ***(b)*** *As in Figure 6a, except averaged over 5 days in late January of a single year.*

Averaging the terms in the salinity conservation equation over a 5˚x5˚ box centered on the salinity maximum and over the winter season (but not vertically integrated as in equation (1)), shows that the individual components of advection exceed other terms by approximately two orders of magnitude within the upper 150 m. The net advection is a small residual, balanced primarily by vertical small scale mixing (including evaporation at the surface) and the salt storage. For this season, the surface evaporative flux tends to increase salinity near the surface, and small scale vertical mixing tends to decrease salinity over the lower half of the mixed layer and increase it below the mixed layer. Advection remains an important term, tending to decrease salinity both within and below the mixed layer. It is apparent from Figure 7b that the net effect of advection, and the directional components in particular, will depend strongly on the choice of the domain of integration.

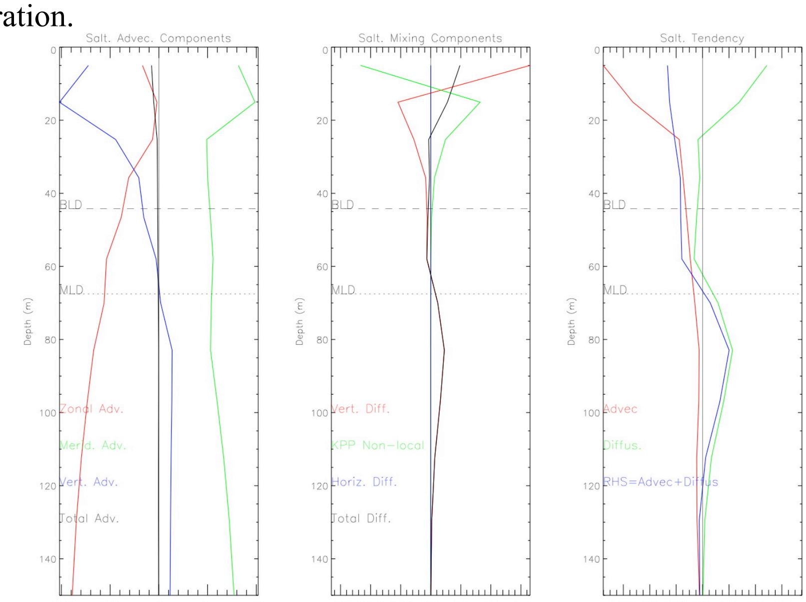


***Figure 8****. Balance of terms in the salinity conservation equation (units $10^{-10}$ sec$^{-1}$) averaged laterally over the region bounded by the grey box in Figure 7a (40°W,20°N to 35°W,25°N) and over the winter season. Left panel: advection components, zonal (red), meridional (green), vertical (blue) and net tendency due to advection (black); Middle panel: small scale mixing components, vertical diffusion (red), non-local mixed layer transport (green), sub-grid scale horizontal mixing (blue), net tendency due to mixing (black); Right panel: net advection (red),*

*net small scale mixing (green), net storage (blue). Horizontal dashed lines indicate two measures of the depth of the mixed layer.*

These estimates are from an unconstrained model integration (i.e., without data assimilation) and thus can only be considered a starting point from which to refine the experimental design. An important element of the outcome of the experiment should be an assessment of the degree to which these estimates of the sizes of individual terms reflect the situation in the real ocean.

**IV SPURS-1: A Subtropical Field and Modeling Program**

*In order to leverage other observational resources associated with the Atlantic Meridional Overturning Circulation program (AMOC Planning team, 2007), we propose that the initial focus of an observational and modeling effort be directed towards the strong sea surface salinity maximum of the subtropical North Atlantic that is subducted into the thermocline and forms the lower limb of the subtropical/tropical shallow overturning circulation (ShallMOC). This region approximately includes the latitudes of 15°- 30°N and 30°-50°W. We call this program Salinity Processes in the Upper-Ocean Regional Study (SPURS), with the overarching goal of assessing the relative importance of all six terms in the eq. 1.*

This location has a number of advantages:

1. high evaporation and low rainfall, making evaporation a dominant component of the salinity balance;
2. a relatively weak large scale geostrophic advective field;
3. relatively weak meso-scale eddies;
4. a straightforward salinity balance, with air-sea flux balanced by vertical and horizontal transport;
5. a spatially and temporally slowly varying salinity field particularly suitable for satellite resolution;
6. the ability to leverage resources from other national and international programs (AMOC, Rapid);
7. convenient access to logistical support.

Research questions to be addressed in SPURS are:

1. What are the physical processes responsible for the location, magnitude and maintenance of the subtropical Atlantic sea surface and subsurface salinity maximum?

- How is S-max formed and dissipated?
- Given the seasonal cycle in (E-P)/h, why there is no seasonal cycle in SSS?
- What processes give rise to the sub-seasonal salinity changes observed at 20°N, 38°W?
- What is the propagation pathway for salt?
- What is the salinity balance of the surface layer on a monthly to seasonal time scale and a regional to meso- spatial scale?

2. How will the ocean respond to changes in thermal and freshwater forcing associated with a changing climate?

- How will the shallow meridional overturning circulation be altered?

3. What is the nature of the cascade of salinity variance from the largest (climate) scales down to dissipation scales of a few millimeters?

4. What new information must be supplied to ocean models in order for these questions to be adequately examined?

To address these questions, an observational and modeling program will be carried out throughout an annual cycle, beginning in early 2012, when the Aquarius satellite will provide near synoptic coverage of SSS. The satellite measurements of Aquarius/SAC-D and SMOS, with resolutions scales of 150-200 km and 7-30 days, will provide the large scale SSS fields surrounding the study region. In combination with surface currents derived from satellite sea surface height and vector wind data (Bonjean and Lagerloef, 2002; see also www.oscar.noaa.gov for information on the surface currents analyses), the satellite SSS data will be used to compute the advective terms (*c* and *d* in Eq. 1), as well as the large scale temporal evolution (term *a*). Preliminary trial balances between steady-state salt advection and *E-P* was studied by Johnson et al. (2002) using climatologic fields. Secondarily, the subtropical study region provides a well measured area with relatively weak SSS variability to monitor the calibration stability of the satellite sensors during the campaign.

In addition to the satellite capabilities, a number of hardware elements of a potential field program in this region can be identified, including ship-based observations: underway data (SST, SSS, Chl-a and hull mounted ADCP); shipboard CTD stations, surface flux measurements, microstructure profilers, and towed SeaSoar capabilities; profiling floats equipped with surface salinity sensors (some with wind speed and rainfall capability, some with microstructure sensors); surface drifters equipped with salinity sensors; gliders (some equipped with microstructure sensors); and at least one mooring heavily instrumented with upper ocean velocity, temperature, and salinity sensors, plus the capability of measuring surface air-sea fluxes. Such field measurements should be complemented by numerical modeling and data assimilation studies in order to best interpret the data collected. The goal of the observational program will be to investigate the dominant governing processes affecting the UOS of the salty subtropical ocean regime, as required to assess all six terms in the eq. 1. We seek to improve our knowledge of horizontal and vertical eddy processes and fluxes (including small scale mixing and stirring), and to improve estimates of *E–P* and surface fluxes in these regions. A fully integrated observing and modeling program involving multiple space/time scales, including the seasonal cycle, synoptic variability, the diurnal cycle and internal tides, is envisioned.

A set of nested experiments is proposed, sponsored by multiple US agencies and with international contributions, designed to sample the characteristics of the salinity maximum region on large scales (2000 km or larger) and scales associated with eddy variability (~200 km and smaller) during the 2012 observational period.

**Large Scale**: This scale covers the entire subtropical ocean regime, with a focus on the region where SSS >37, where the this isohaline surface forms the unique subtropical high salinity bowl. The large-scale assessment of this region would rely chiefly on the present coverage of satellites, ship-based sections, floats, and drifters, but with enhancements to XBT/XCTD lines and Argo float coverage for improved resolution to provide context to the observations within the mesoscale ~200 km box. More specifically, the observational enhancements include: surface temperature and salinity resolving (STS) Argo floats; the addition of salinity sensors to surface drifters; met/flux sensors added to the nearby Pirata mooring; and SOOP/VOS observations. Floats and gliders are to be deployed to estimate the volume of water contained in the high salinity bowl as well as to examine mixing inside and through this control volume ("the river of salt") downstream from the outcropping region. Aquarius data will be used to provide near synoptic coverage of the SSS within the large scale component of SPURS.

A comparative study (Atlantic S-max vs other S-max) using existing observing systems and global models wills be carried out in order to provide a global scale context and linkage to the global water cycle.

**Mesoscale**: The highest resolution is within two 200 km boxes, one centered on the salinity maximum in the N. Atlantic (the outcropping region) and one centered approximately 10° of latitude to the south of the maximum (the edge of the SSS > 37 region that marks the high salinity bowl), where the surface salinity gradients are large and $E-P$ is a maximum. Within the mesoscale box observations will resolve horizontal scales from <10 km to the full 200 km scope of the box. The observational program may include:

• Ship-based underway thermosalinograph and undulating profiler measurements; ADCP, XBT/XCTD transects; AUV work; ASIP; PAL; and microstructure profilers.

• Ship deployment of gliders, surface drifters, EM-APEX. A possible approach is a year-long glider survey that connects the 2 mesoscale boxes, carried out by ~8 gliders. The surface drifters can be enhanced with ADCP and wind sensors, to determine the surface structure.

• The use of profiling floats (30 km resolution in each box) and gliders, some equipped with microstructure and/or EM sensors, to determine the near surface and subsurface structure.

• Flux buoys (one located south of the S-max, where the biggest differences in surface flux estimates is found, and acoustic wind observations from floats and gliders.

• Estimates of eddy fluxes from a central flux mooring in each box. In the northern box, this requires a new flux mooring; in the southern box, the use of a Pirata mooring already in place can be used (enhancements to its sensor suite might be required)

**Small-scale:** (<10 km), < 1 day. Here the effort would be dedicated to estimation of the microscale dissipation parameters $\varepsilon$ and $\chi$ in as many places as possible using enhanced gliders, profiling floats, and shipboard measurements. The focus would be on sub-mesoscale and internal/inertial-wave induced mixing and processes such as salt fingers. The surface skin can be studied with upward-going profilers. The data will be used to make estimates of turbulent mixing at scales from several hundred kilometers down to the dissipation scale of millimeters.

**Modeling Component:** SPURS is a fully integrated observing and modeling program. Before the field experiment, SPURS will use models to perform Observing System Simulation Experiments (OSSEs) to aid the observing system design. During the field experiment, SPURS investigators will have access to real-time assimilative/forecasting models at the spatial scales of observational data being collected. After the field experiment, models will be used to produce reanalysis to further address the SPURS science questions.

The models, in conjunction with the field data collected, can be used to examine the dynamics and thermodynamics of the salinity maximum region, the role of freshwater sources from the south of the maximum region, and the role of surface fluxes, subduction, and eddies in determining the time-dependent 3D structure of salinity. The synthesis of the understanding developed through the combination of process modeling, analysis of the observations, and more comprehensive modeling of the salinity maximum region and its connections to the basin- and global-scale circulation will lead to advanced parameterizations of salinity stirring and mixing for use in global climate models. Real-time data assimilation is important in this work. The model program may include:

- Process-oriented ocean models, including large-eddy-simulation (LES), to address specific SSS processes, e.g., mixing parameterizations
- Full 3D OGCMs: multi-scale models from global to regional
- Pre-field experiment: OSSE, observing system design, trade-off studies (e.g., how many gliders do we need to address a specific science question?)
- During the field experiment: real-time or near-real-time assimilation/forecasting, adaptive sampling (feature tracking: eddy, front, salt river, 37 PSU contour)
- Post-field experiment: reanalysis, further process modeling, parameterization development
- Air-sea fluxes from global NWP models may not be accurate enough, so a downscaled WRF/COAMPS nowcast/forecast/reanalysis over the field experiment domain is likely to be needed; leverage on NCEP, NCAR and NRL-MRY may be required.

## V. Resources Required

The temperature, salinity, and velocity fields consist of large-scale signals (> 200 km; > 30 days), eddy-scale signals (10-200 km; 1-30 days), and smaller scale signals (< 10 km; < 1 day). The satellite and surface drifters will likely do a good job of measuring the large-scale sea surface salinity and velocity signals, and floats and gliders can be used to extend these measurements into the subsurface ocean. The small-scale signals can be measured using ship-based microstructure observations and possibly from microstructure sensors mounted on gliders or floats. Temporal variability of air-sea fluxes of heat and freshwater can be inferred from a well-instrumented central flux mooring (costs probably prohibit more than one of these at best). Yet while the eddy energy is purportedly weak in this region (recall that rms non-seasonal sea level variability is under 3 cm), the eddy *fluxes* (and flux divergences) of heat, salt, and momentum are relatively unknown and might make a substantial contribution to the evolution of salinity as modeled by (1).

It is possible to envision an experiment where the salinity, temperature, and velocity are resolved at the largest horizontal scales by the satellites and an array of profiling floats and surface drifters, which can be used to produce maps of the relevant quantities at scales of 200-1000 km. This might require 30-40 floats and a similar number of drifters, with the *in situ* observations used for mapping between the sea surface and some deeper level, perhaps 1000 m (with this choice of parking depth the floats will disperse quite slowly in this region). By using the float drift velocity at 1000 m in conjunction with float-derived dynamic height estimates, the absolute geostrophic circulation on 200-1000 km scales in the region, from the surface to 1000 m, can be determined. The float and drifter data can also be used for validation of the satellite measurements, and if equipped with wind and rainfall capability the floats can be used in estimation of surface fluxes. The float array, especially, should also provide important information concerning questions 4 and 5 from above: as high salinity surface water is subducted and spreads south and west, some of the floats can be reprogrammed into an isopycnal mode (using Iridium communications) in order to follow the high salinity subducted plume.

The Aquarius/SAC-D and SMOS satellites will be a key component of this effort. With a footprint of ~100 km , the satellite will do little to improve estimates of the eddy or small-scale mixing components of this work, but satellite data could provide the best estimate of surface salinity and horizontal gradients at the mesoscale and larger (Figure 9). Satellite based wind and precipitation estimates will be useful in determining surface fluxes at the largest scales. Estimates of precipitation from Aquarius (in conjunction with TRMM and profiling float-based estimates) should help to provide good measurements of rainfall on daily time scales and spatial scales of 25 km or so in the study region. Additionally, the surface flux climatology in this region is likely to prove invaluable in the field effort. Estimating the Ekman downwelling ($w_{-h}$ in term *d* in (1)) can probably best be done through a combination of climatological winds, estimates from the Aquarius scatterometer, climatological winds, and estimates derived from profiling floats equipped with wind sensors. As shown by O'Conner et al. (2005), the climatological winds from this region are good enough to make credible estimates of the Ekman pumping velocity and subduction rates at the largest scales; with the several methods available to estimate winds in this experiment, we should be able to improve upon those results.

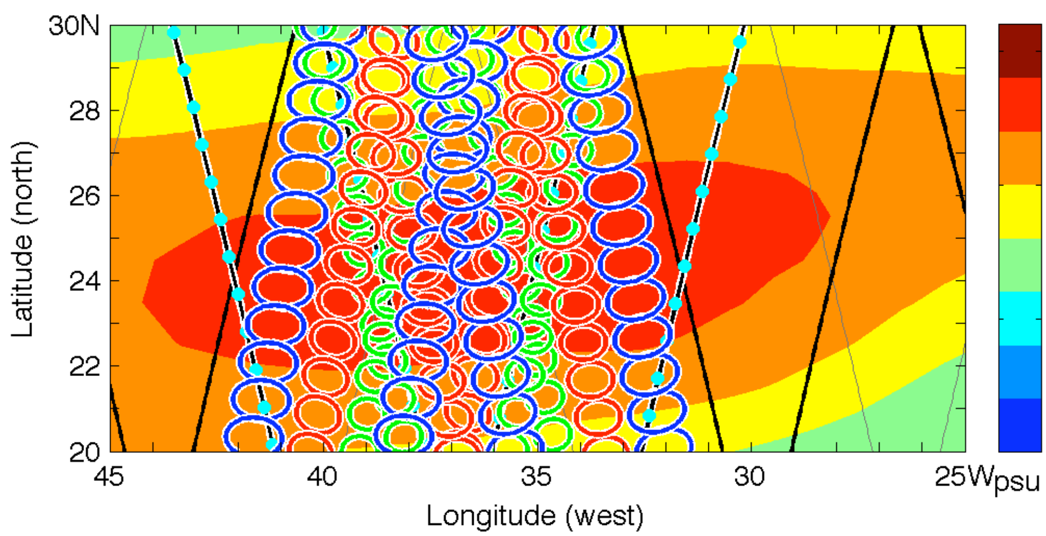


***Figure 9**. Subset of the Aquarius 3-beam swath over the North Atlantic climatologic surface salinity maximum region. The green, red and blue ellipses are the inner, middle and outer beams, semi-major axes 94 km, 120 km, 156 km, respectively, shown every 14.4 seconds (~100 km) along the orbit. Solid lines (light and dark) represent the sub-satellite tracks; blue dots show representative 14.4-second along-track intervals. The science data record will contain samples every 1.44 seconds.*

Estimation of the eddy contributions to (1) is through the use of eddy-resolving numerical models with data assimilation. One can imagine initializing the model with measurements from the float and drifter array and conducting free simulations to estimate the importance of eddy fluxes. Note that it is probably not necessary to reproduce the actual eddy field exactly in the model, only to make a valid estimate of the eddy variability and eddy fluxes that can be used to compare against the other measurements in (1) and the values of the fluxes through the lateral boundaries of the study region. Additionally the observations may be assimilated into an eddy-resolving model in order to produce a 'best estimate' of the evolving state variables and fluxes. The gridded fields resulting from such an exercise would be one of the products of this process study and would provide considerable information about the uncertainties of the estimates. A variety of assimilation/state estimation techniques have been developed and can be explored in this context. Because of the ability of modeling/assimilation activities to extend the value of the observations, provide context, and provide information about uncertainties, it is recommended that a strong modeling/data assimilation project be carried out in parallel to the field program.

Gliders, while perhaps not yet practical as a tool for estimating boundary fluxes, nevertheless have an important role to play. A fleet of long-lived gliders could be used to enhance the mapping capabilities of the float and surface drifter array. They are envisioned to repeatedly occupy two butterfly-type regions to determine the long-term geostrophic mean fields. Short-term gliders would be deployed during the cruises and be equipped with microstructure sensors to estimate small scale mixing (term $f$ in (1)) over a large part of the study region over the course of several months. Addition of microstructure sensors to Webb gliders has already been done and the technology should be mature within a year or two. This would appear to be a cost effective means of measuring mixing rates during the periods when no shipboard estimates are available.

An important requirement for such an experiment is the estimation of surface fluxes of heat and freshwater. The quantities can be estimated from research vessels, although it is likely that ships will only be in the study region for a small fraction of the total time that the experiment is underway. These fluxes can likely be well-estimated at a dedicated flux mooring installed in the center of the study region (an expensive, but seemingly necessary component); these estimates will be critical to the success of the program. The near-surface salinity/temperature measurements from floats, coupled with the wind/rainfall measurements, can possibly be used to make some estimates of heat and freshwater fluxes, but other means (again, models) will have to be used to infer the values across much of the array and provide a context for interpretation of the estimates. Flux estimates will also be an outcome of the modeling/assimilation experiments.

A more specific listing of required resources includes:

**• Support of our current capabilities (Figure 10)**

–Satellites (e.g., SMOS/Aquarius, GHRSST, Jason-1/2/Envisat, TRMM/AMSRE, ASCAT)
–Ocean observing system: Surface drifters, Argo floats, XBT (AX07/08), TSG from SOOP/VOS, XBT
–Value-added products (e.g., GPCP, OAFlux,…)
–Access to highest possible resolution NWP analysis/reanalysis (NCEP, ECMWF)
–Global ocean model analysis/reanalysis (e.g., POP, ECCO, NCOM/HYCOM)

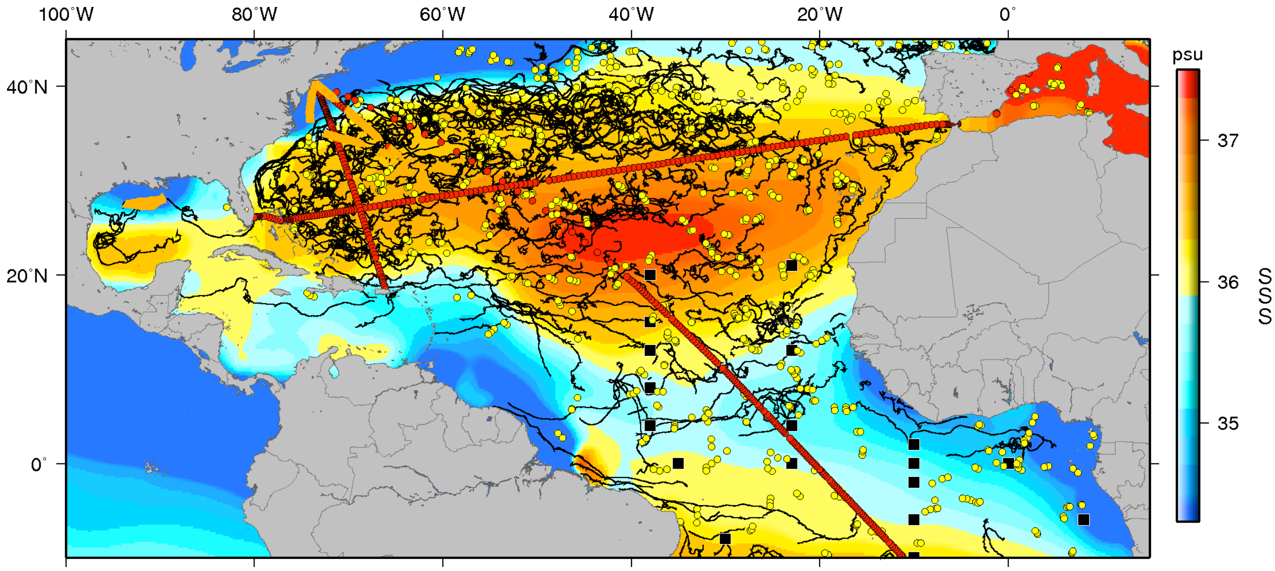


***Figure 10**. Existing ocean observing resources in the subtropical North Atlantic with sea surface salinity. Black =drifter trajectories are for Dec 2008 – May 2009; Yellow = Argo locations are for November 2009; Red = High Density XBT transects, summer 2009; Orange = TSGs, November 2009; Black Squares = Pirata moorings.*

**• Enhancement of current capabilities**
–STS Argo floats (~80; 40 in each 200 km box), salinity surface drifters (~55), added flux sensor on Pirata mooring, ADCP equipped surface drifters.

**• SPURS-1 observing program:**

(1) 3-4 months of dedicated ship time (medium class) over the course of 1 year, to be used for CTD/$O_2$ and microstructure profilers; underway surface and ADCP measurements; moored and drifting instrument deployment and recovery; and *in situ* measurements of surface fluxes and other environmental parameters. Some ship time may be available from Ireland, Spain or Germany.

(2) ~4-8 Seagliders for occupation of the butterfly boxes,

(3) ~12 mesoscale gliders and more AUVs (Spray, Slocum, Remus) some equipped with microstructure sensors,

(4) microstructure profilers including surface skin profilers such as ASIP, several EM profiling floats for examining mixing associated with inertial motions, temperature and shear microstructure capability on profiling floats. Salinity microstructure capability on profiler, floats and gliders (under development).

(5) A well-instrumented surface flux mooring, in place for at least one year, and densely instrumented with *T*, *S*, and velocity sensors in the upper 500 m,

(6) A towed ship-based profiling CTD and ADCP,

(7) Multiple scale (global/basin/region) 3-dimensional eddy-resolving ocean models with data assimilation capabilities over the selected field experiment region to support pre-FE OSSEs, real-time operations and post-experiment reanalysis. Also process models are required to test parameterizations as well as mesoscale atmospheric models for improved estimates of air-sea fluxes.

**• SPURS Information System**

The success of the SPURS field experiment depends on the collaboration of a network of institutions geographically spread across the country and from countries on both coasts of the Atlantic Ocean. The objectives require quantitative analysis of interdisciplinary data sets and model output. Thus, observational data and model output must be exchanged between researchers. To extract the full scientific value, data must be made available to the scientific community on a timely basis.

A SPURS information system (SPURSIS) will be established well in advance of the field experiment to collect data/products, make them available through the web, and will archive all versions of data. Originators (observing elements or modeling groups) will be primarily responsible for quality control of their own data/products. As soon as data might be useful to other researchers, the data will be released, along with documentation that can be used by the user community to judge data quality and potential usefulness.

The intellectual investment and time committed to the collection of a data set entitles the investigator to the fundamental benefits of the data set. Therefore, publication of descriptive or interpretive results derived immediately and directly from the data is the privilege and responsibility of the investigators who collect the data. Publication of the data and model output may require a citation, contact with the providers, or in some cases permission from the providers.

Combination and integration of the data collected is an important aspect of SPURS. Thus, it will be incumbent upon SPURS PIs to make their data quickly available to other SPURS PIs, and eventually to the oceanographic community at large. SPURSIS will be designed and set up to facilitate sharing of data, with controlled permissions, readily available quality control flags, standardized formats and embedded metadata. SPURSIS will be made available to PIs working at sea to the extent that it is feasible.

**• Additional required elements:**

• Data upload/download: historical, real-time and archival activities
–Observational data (many types, different formats)
–Model output (huge volume)
• Communication and coordination (planning before field experiment; command and control during the field experiment)
• Global comparative study of S-max regions

*SPURS*

• Mesoscale atmospheric models (leveraging from NCAR and NRL-MRY)
• Potential interests to non-PO communities (e.g., biogeochemistry, CO2 flux)
• Synergy with other programs: AMOC, CLIVAR, GEWEX, SAMOS, a WMO pilot project
• Liaison with related European programs

## V. Summary

No single element of the climate system has as much impact on society as the water cycle, yet the seemingly most important parts of this cycle occur over the vast and undersampled ocean. Here we have proposed to begin a process of improving our basic understanding of the water cycle over the oceans with an initial field study of the processes controlling the formation of the subtropical surface salinity maximum. This experiment, SPURS-1, is timely because it draws on recent (Argo) and anticipated (Aquarius) advances in oceanic salinity observational capabilities. It also will lay the foundation for improved ocean modeling of the processes affecting salinity. At a later time we hope to perform a similar field experiment (SPURS-2) in a region of strong precipitation, where quite different mixing processes will prevail. By examining these salty and fresh end-members, the SPURS program will improve understanding of the processes contributing to the production of salinity variance in the ocean, and its impact on ocean mixing, circulation and climate.

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