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Sea Surface Salinity Observations with Lagrangian Drifters in the Tropical North Atlantic During SPURS

Circulation, Fluxes, and Comparisons with Remotely Sensed Salinity from Aquarius

By Luca R. Centurioni, Verena Hormann, Yi Chao, Gilles Reverdin, Jordi Font, and Dong-Kyu Lee

"This paper provides an overview of a major observational effort funded by the National Oceanic and Atmospheric Administration (NOAA) and NASA to observe SSS in the SPURS-1 region during approximately two years with a large array of Surface Velocity Program (SVP) drifters drogued at 15 m depth and equipped with salinity and/or temperature sensors."

ABSTRACT. The Global Drifter Program deployed a total of 144 Lagrangian drifters drogued at 15 m depth, including 88 equipped with salinity sensors, in support of the first Salinity Processes in the Upper-ocean Regional Study (SPURS-1) in the subtropical North Atlantic Ocean with the goal of measuring salt fluxes associated with surface currents. The quality-controlled data set consists of 996,583 salinity observations collected between August 2012 and April 2014. A comparison of the drifter salinities with Aquarius satellite sea surface salinity (SSS) data shows that the lifespan of the salinity sensor fitted to the drifters is of the order of one year. The salinity and velocity data from the drifters were used to validate salt transport divergence computed with satellite products, with satellite salinity taken from the standard Aquarius v3.0 data set. The results indicate good agreement between the two independent methods, and also demonstrate that the effect of the eddy field combined with SSS variability at the surface dominates the signal. SSS variability within spatial bins as compared to Aquarius-beam footprints measured by drifters can be in excess of 0.1 psu. This result suggests that careful evaluation of the representation error is required when single-point in situ measurements, such as those collected by Argo floats, are used to validate spatially averaged Aquarius salinity data.

INTRODUCTION

The distribution of salinity in the ocean is an important indicator of the global water cycle (see Schmitt, 2008, for a review). Because the processes that determine ocean salinity distribution are not well measured over most of the ocean, CLIVAR (Climate Variability and Predictability) recommended that a Salinity Processes in the Upper-ocean Regional Study (SPURS) be conducted during the active lives of the Aquarius (Lagerloef et al., 2008) and Soil Moisture and Ocean Salinity (SMOS; Font et al., 2010) sea surface salinity (SSS) satellite missions.

In December 2009, a National Aeronautics and Space Administration/National Science Foundation (NASA/NSF) sponsored planning meeting for SPURS chose the center of the salinity maximum in the subtropical North Atlantic Ocean and its southern boundary for regional studies to begin in fall 2012 (SPURS-1; http://spurs.jpl.nasa.gov). A compelling long-term objective of SPURS has been to understand and quantify the processes that control SSS distribution in the subtropical North Atlantic Ocean in order to elucidate the link between observed SSS trends and amplifications of the water cycle on interannual and longer time scales (Durack and Wijffels, 2010; Durack et al., 2012). Another major goal of SPURS has been to quantify the spatial and temporal variability of SSS and the terms of the near-surface salinity budget on horizontal scales smaller than those resolved by Aquarius (hereinafter referred to as subgrid scale), which was designed to measure SSS with three beams generating footprints on the ground ranging from 60 km to 150 km in width.

This paper provides an overview of a major observational effort funded by the National Oceanic and Atmospheric Administration (NOAA) and NASA to observe SSS in the SPURS-1 region during approximately two years with a large array of Surface Velocity Program (SVP) drifters drogued at 15 m depth and equipped with salinity and/or temperature sensors. In addition to describing the experiment and methodology, this paper addresses two topics. First, we use the drifter-derived data set along with satellite-borne observations of sea level and SSS to compute the seasonally changing variability of the ocean circulation in the SPURS-1 region and the divergence of the transport (or fluxes per unit area) of salt. Second, we discuss the performance of the salinity drifters (SVPSs), with particular focus on delayed-mode, quality-control procedures used to evaluate the salinity data and the useful lifespan of the measurements. We also briefly discuss the subgrid-scale variability of SSS estimated from the drifters and how it can affect validation of the Aquarius SSS products.

THE SSS MAXIMUM OF THE SUBTROPICAL NORTH ATLANTIC OCEAN

Near-surface ocean dynamical and air-sea interaction processes in the subtropical North Atlantic produce a vast area of high-salinity surface water that is centered at about 25.5°N, 36.5°W, fluctuates with seasons (Gordon and Giulivi, 2014), and exhibits a meridional displacement with maximum northward excursion observed in summer (Dessier and Donguy, 1994; Reverdin et al., 2007b). On interannual and longer time scales, the SSS of the subtropical North Atlantic shows a positive trend (Dessier and Donguy, 1994; Durack et al., 2012).

In the salinity maximum region, the mean horizontal advection processes in the mixed layer are small due to weak mean horizontal salinity gradients. The seasonal mixed-layer salinity budget in this region is thought to be balanced by fluxes at the air-sea interface, vertical diffusion, and Ekman transport (Moisan and Niiler, 1998). The additional contribution horizontal eddy salt fluxes make to the salinity budget was poorly quantified before SPURS. The drifter experiment described here represents one of the first attempts to measure them with direct and concurrent observations of SSS and mixed-layer currents.

The three-dimensional circulation in the SSS maximum region is characterized by southward-flowing subducting waters (Snowden and Molinari, 2003; Schott et al., 2004) and, south of the latitude of the SSS maximum, by northwestward-flowing surface waters originating from equatorial upwelling and wind-induced Ekman transport in the trade wind region (Schott et al., 2004), as also confirmed by drifter observations collected before the SPURS experiment (Figure 1A,C). This three-dimensional current regime is the basis of shallow overturning circulation in Atlantic Ocean subtropical/tropical waters, and the same phenomenon is found in the Pacific Ocean (Schott et al., 2004). The surface geostrophic velocity across the SPURS-1 region computed from NOAA's 2005 World Ocean Atlas is toward the equator (stars in Figure 1C), while the 15 m total velocity (from the drifters) is predominantly to the northwest and west (blue and red dots in Figure 1C). The geostrophic circulation below the North Atlantic SSS maximum is southwestward (Figure 1B and red triangles in Figure 1C; note also the reduction of the horizontal extent of the salinity maximum at this level compared to that at the surface in panel A); it shows a spiral of geostrophic velocities that rotates counterclockwise with

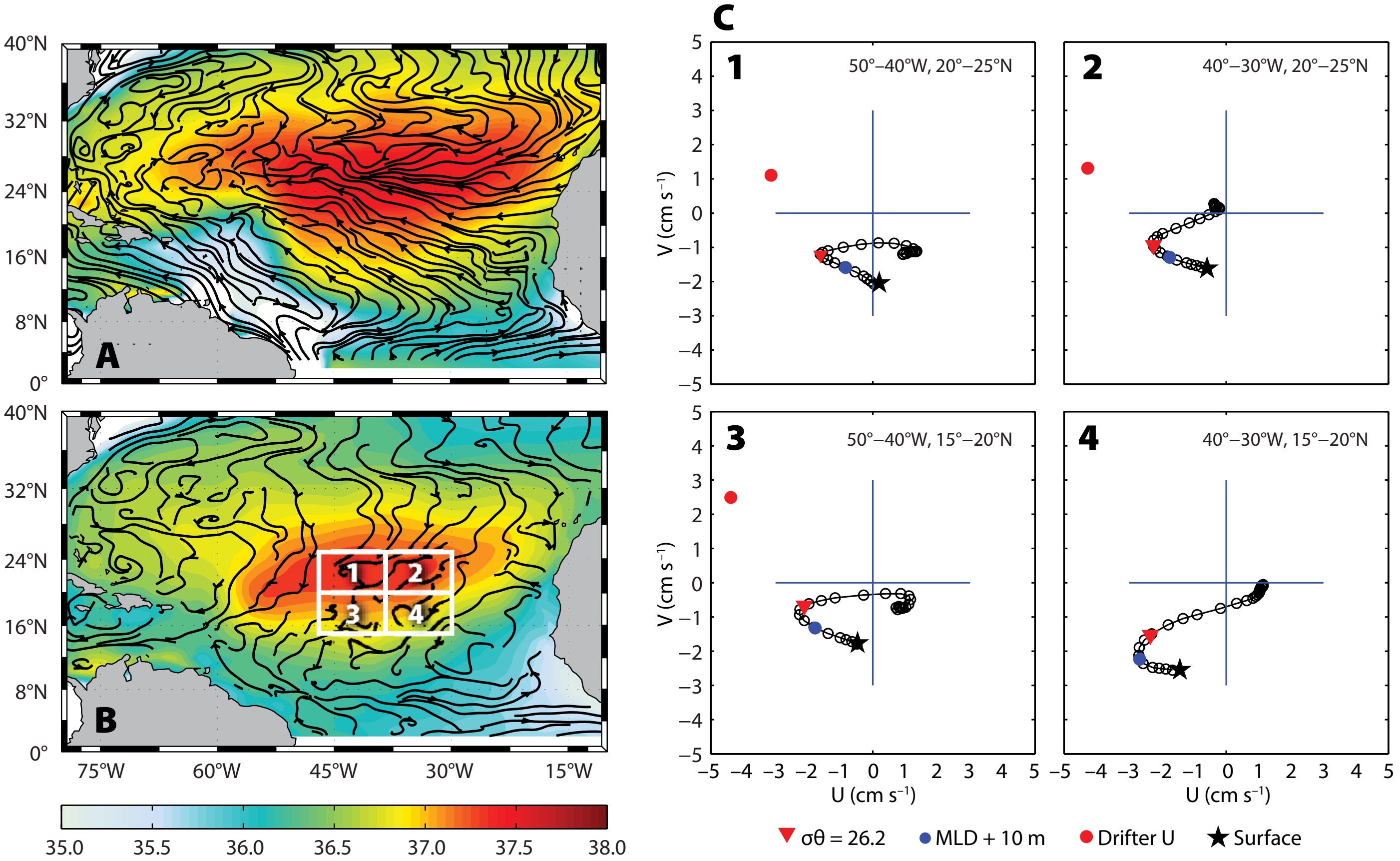

FIGURE 1. (A) Sea surface salinity (SSS) from NOAA's 2005 World Ocean Atlas overlain with the 15 m depth streamlines derived from the historical drifter data set (October to December period, from October 1997 through December 2008). Both quantities are averaged at 1° spatial resolution. (B) Absolute geostrophic streamlines for the same period below the mixed-layer depth (MLD +10 m). Gray boxes 1 and 2 loosely denote the area were most of the drifters were deployed. (C) The fall period absolute geostrophic hodographs referenced to surface sea level (Maximenko et al., 2009). The red "dot" is the averaged 15 m velocity from drifter data (viz. Centurioni et al., 2009). The averaged geostrophic currents were computed from NOAA's 2005 World Ocean Atlas, and the standard depths (0, 10, 20, 30, 50, 75, 100, 150, 200, 250, 300 m in the upper ocean) are designated and labeled in panel B.

TABLE 1. Specifications of the Surface Velocity Program drifter with a salinity sensor (SVPS).

Tracking System	Location Accuracy	Overall Length	Depth at Center of Drogue	Nominal Lifespan	Sea Surface Conductivity Accuracy	Sea Surface Temperature Accuracy
Argos III & GPS	Argos: 300–1,000 m GPS: 5 m, 2DRMS*	~19 m	15	>2 years	0.0003 S m^{-1}	0.002°C

*2DRMS = Twice the distance root mean square

decreasing depth (Figure 1C). Figure 1C further indicates that geostrophic shear within the upper ocean can be as large as 30% of the implied wind-driven shear, and in general is in the opposite direction. This implies that wind-driven currents must cancel the geostrophic shear to the southeast in the process of driving a near-surface current to the northwest. Ekman dynamics thus play a central role in shaping the SSS maximum of the subtropical North Atlantic.

THE SPURS DRIFTER EXPERIMENT

The drifter experiment was designed primarily to measure subgrid horizontal transports of salt and SSS variability. Drifter-derived estimates of these quantities could then be used to validate corresponding satellite-derived computations, with the objective of expanding them to the entire high-SSS region of the subtropics. Figure 1 clearly demonstrates that the near-surface circulation passes through the salinity maximum from east to west, first increasing the salt ion concentration as a result of evaporation and then decreasing the concentration along streamlines by either vertical mixing with less-salty water from below or horizontal mixing with the less-salty water that surrounds the high evaporation region. Drifter observations (Maximenko et al., 2009) show that there is a broad surface eddy kinetic energy (EKE) minimum surrounding the eastern portion of the salinity maximum, but as the surface streamlines pass westward of 40°W, the EKE increases, thus providing a possible mechanism for sustaining lateral eddy fluxes.

Eighty-eight SVPS drifters (Reverdin et al., 2007a) and 56 SVP drifters (Niiler, 2001) were deployed in the subtropical North Atlantic Ocean near 25°N, 38°W to measure SSS and near-surface currents, representing NOAA's contribution to the SPURS experiment. The choice of this location, which is near the rim of the near-surface EKE low, represented a trade-off between the synergistic use of closely located and concurrent SSS observations collected by other SPURS investigators to validate Aquarius SSS retrievals and our science goals. The purpose of deploying 56 SVP drifters in addition to the 88 SVPS drifters was to improve the representation of the ocean currents and associated variability, and consequently improve the computation of the surface freshwater fluxes. This study does not include an additional 26 SVPS drifters deployed in the region by French and Spanish investigators.

The SVP and SVPS drifters are designed to measure water velocity in a Lagrangian sense at a depth of 15 m (i.e., within the surface mixed layer), SSS, and sea surface temperature (SST) at a depth of approximately 0.5 m. The SVP drifters measure water velocity in the same fashion as the SVPS drifters, and SST at a depth of a few centimeters below the ocean surface. The velocity measurements are accurate to within 0.01 m s^{-1} for winds up to 10 m s^{-1} (Niiler, 2001; Maximenko et al., 2013).

Table 1 provides the main specifications of the SVPS drifters, which were programmed to acquire their Global Positioning System (GPS) locations and measure SSS every 30 minutes. In terms of the SSS observations, the duty cycle of the SVPS drifters manufactured by Pacific Gyre Inc. has been as follows: the salinity sensor (SBE37-SI) was polled for instantaneous sampling once a minute for five minutes at the beginning of each 30-minute transmit cycle. The average of the five measured values was then transmitted.

The SVP drifters have a less accurate SST sensor (±0.1°C) than the SVPS version and are tracked with the Argos satellite system, which uses the Doppler-shift method and a Kalman-filter algorithm to determine drifter locations (Lopez et al., 2014). The Argos localization methodology yields much less accurate positions (of the order of ±300 m) compared to the GPS technique, but it is sufficient to resolve the variability of the ocean's mesoscale currents.

The drifter deployment strategy was refined upon analysis of the historical drifter velocity data. The computation of the drifter's residence time in a 210 km × 210 km box centered at 24.5°N, 38°W from the historical drifter data set indicated that it would take approximately 1.5 months for a drifter array, moving to the northeast with an average speed of 3.6 cm s^{-1}, to leave the box. It was therefore decided to deploy the SVPS drifters with monthly frequency during the first year of the experiment, taking advantage of deployment opportunities offered by the SPURS-1 cruises and several Voluntary Observing Ships (VOS). Table 2 lists the complete deployment of Global Drifter Program (GDP) drifters. Figure 2 shows a map of the deployment locations.

The deployment strategy for the SVPS drifters was modified in year two due to the lack of VOS opportunities. Most of the SVPS drifters (36) were deployed during the Spanish MIDAS (Managing Impacts of Deep Sea Resource Exploitation) cruise, and six additional drifters during an R/V *Endeavour* cruise in March–April 2013.

The first drifter deployments occurred from August 21 through August 27, 2012 (STRASSE cruise, see Reverdin et al., 2015, in this issue, for a more detailed description of this experiment's module) and continued through July 11, 2014. Most of the drifters were deployed near the SPURS-1 core region where the moorings and gliders were also operating (black box in Figure 2). A total of 156 SVP drifters operated in the subtropical North Atlantic, 56 of which were deployed in the SPURS-1 region as part of this effort. Five SVPS drifters failed upon deployment (see Reverdin et al., 2014). As anticipated, the drifters moved primarily westward and filled a substantial portion of the SSS maximum region (Figure 2, red tracks).

The drifter data were transmitted through either the Argos or the Iridium satellite systems and posted in real time to the Global Telecommunication System (GTS) of the World Weather Watch; they were also made available to the SPURS-1 team in real time after passing an automated quality-control filter designed to remove unrealistic spikes.

TABLE 2. List of drifter deployments. SVP = Surface Velocity Program drifter. SVPS = SVP drifter with a salinity sensor. GDP = Global Drifter Program.

Ship — Cruise	SVPS	SVP	Deployment Times
R/V *Thalassa* — STRASSE[1]	10	10	8/21–8/27/2012
R/V *Knorr* — SPURS-1	18	-	9/17–10/3/2012
RRS *Discovery* — RAPID[2]	9	-	10/04/2012
MN *Colibrí*	3	-	11/27–11/28/2012
R/V *Sarmiento* — MIDAS[3]	36	-	16/3–17/4/2013
MN *Colibrí*	-	10	3/28–3/30/2013
MN *Colibrí*	-	2	4/10–4/11/2013
R/V *Endeavour* — EN522	6	-	3/19–4/5/2013
R/V *L'Atalante*	-	6	5/29–5/30/2013
MN *Colibrí*	-	8	7/14–7/15/2013
MN *Toucan*	-	5	10/12/2013
Sailing Vessel *Gamin*	6	-	10/27/2013
MN *Colibrí*	-	5	12/8–12/9/2103
MN *Colibrí*	-	5	4/23–4/24/2014
MN *Colibrí*	-	5	7/10–7/11/2014
Total number of GDP drifters deployed for SPURS	**88**	**56**	

[1] Sub-Tropical Atlantic Surface Salinity Experiment

[2] RAPID Climate Change - Atlantic Meridional Overturning Circulation

[3] Managing Impacts of Deep Sea Resource Exploitation

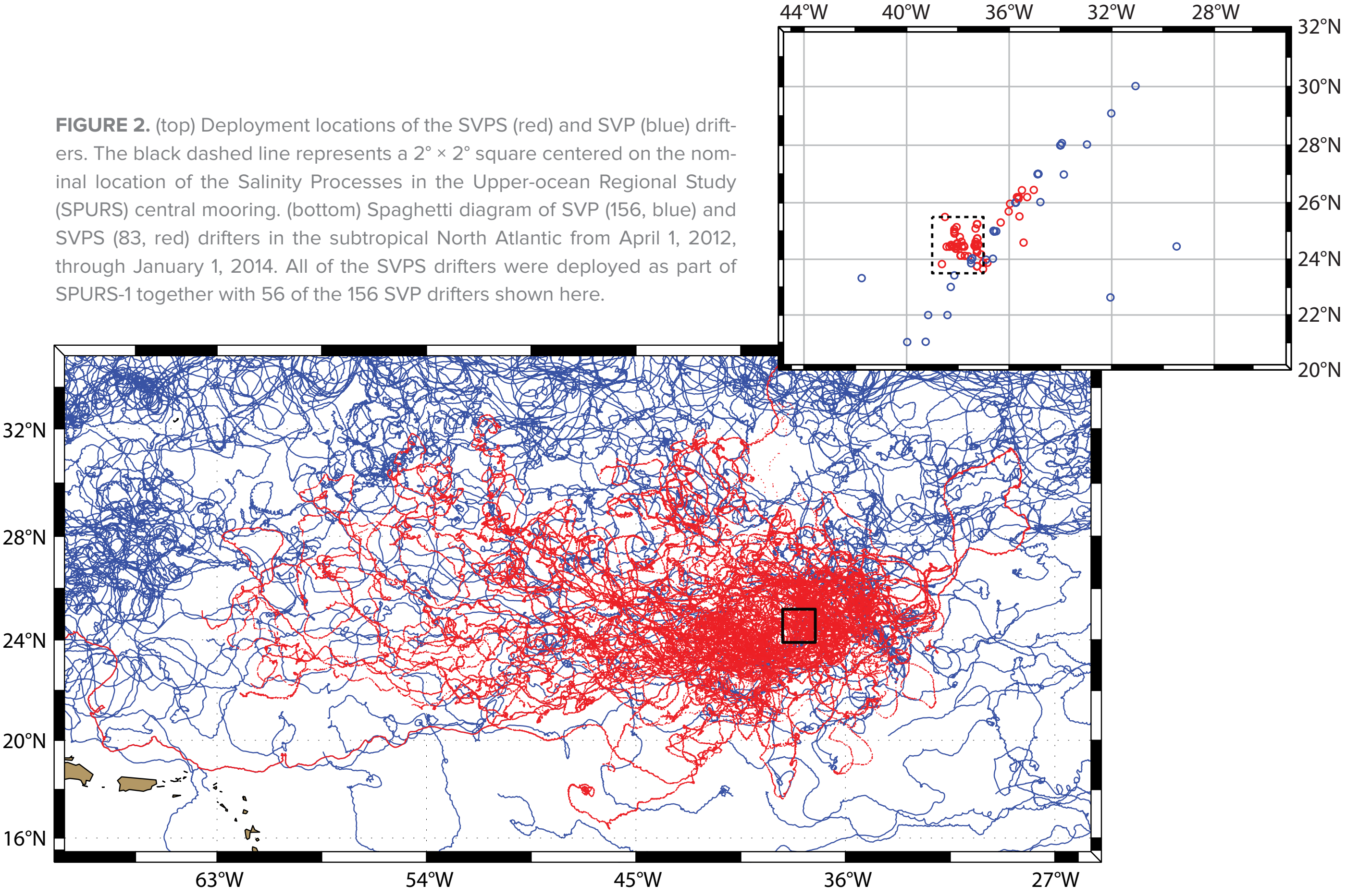

FIGURE 2. (top) Deployment locations of the SVPS (red) and SVP (blue) drifters. The black dashed line represents a 2° × 2° square centered on the nominal location of the Salinity Processes in the Upper-ocean Regional Study (SPURS) central mooring. (bottom) Spaghetti diagram of SVP (156, blue) and SVPS (83, red) drifters in the subtropical North Atlantic from April 1, 2012, through January 1, 2014. All of the SVPS drifters were deployed as part of SPURS-1 together with 56 of the 156 SVP drifters shown here.

In delayed mode, the drifter positions were first quality controlled and then a Kriging interpolation algorithm was applied to obtain six-hourly, regularly spaced drifter location time series (Hansen and Poulain, 1996) from which the drifter velocities were obtained using 12-hour centered differences. A wind slip correction was also applied (Niiler et al., 1995) to the velocity data. Velocities from drifters that had lost their drogues were further recovered as described in Pazan and Niiler (2001). Tidal and shorter period velocities were filtered out with a 36-hour boxcar filter of unit amplitude applied along the drifter tracks, centered at the time of the observations.

QUALITY CONTROL AND PERFORMANCE OF THE SVPS DRIFTERS

Previous studies have described the SVPS drifter technology (Reverdin et al., 2007a); discussed quality-control (QC) algorithms to edit the salinity data for incorrect values, biases, and spikes (e.g., Reverdin et al., 2014); and concluded that the useful time span of the salinity sensor is of the order of about six months. This value was obtained after most of the incorrect salinity data were edited using a sequence of filters designed, among other things, to discard data associated with large values of the standard deviation used as a threshold criterion to remove spikes and noise.

The SPURS drifter experiment was designed to include several cluster releases to facilitate, among other scientific goals, the intercomparison of SSS from different sensors for calibration purposes. Through inspection of SSS observations of nearby drifters and Argo floats, it was found that the main source of noise and bias in the SSS data originates from the algorithm used by the drifters to average the salinity that is transmitted via satellite (i.e., the straight average of five salinity samples taken one minute apart over five minutes; Hormann et al., 2014). Such an averaging method introduces a bias toward fresher SSS values due to lower conductivity measurements originating from air bubbles trapped in the measuring cell of the conductivity sensor. When erroneous measurements are averaged together with good ones, the bias induced by the air bubbles cannot be removed during pre-analysis because only the averages are transmitted. It is very difficult to implement an automatic QC filter because the SSS noise level can be highly variable depending on how many bubbles are present and how many incorrect values are included in the average. Thus, it was determined that this QC step needs to be implemented manually (Hormann et al., 2014). It was found that minimal editing and de-spiking was needed after the manual data cleanup and that several of the spikes that could have been interpreted as erroneous values were instead real because they were confirmed by nearby drifters (Figure 3), Argo floats, and Aquarius, or they were determined to be associated with rain events (Hormann et al., 2014). A total of 996,583 (out of 1,077,613) SSS measurements collected between August 2012 and April

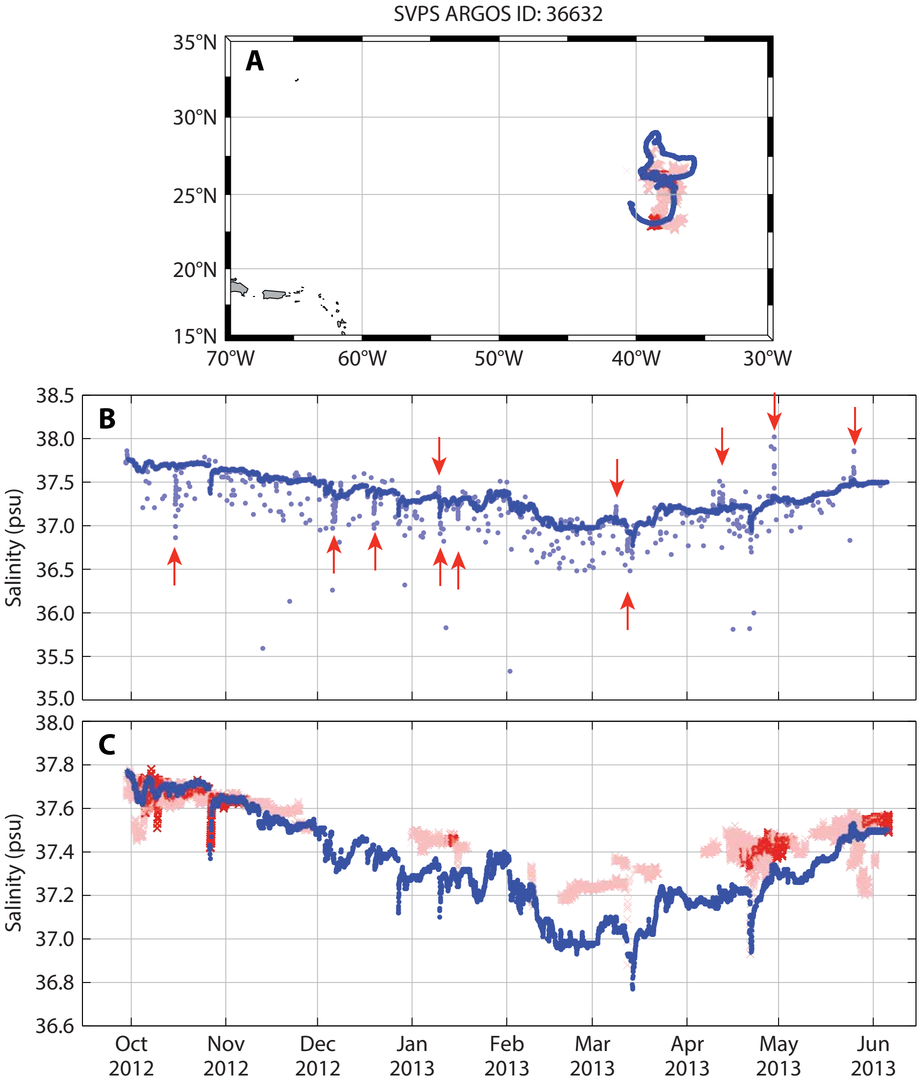

FIGURE 3. (A) Track of an SVPS drifter, Argos ID 36632, deployed from R/V *Knorr* during the SPURS cruise in September 2012 (blue), and locations of nearby drifters separated in time by ±6 hours and within 100 km (light red) or 50 km (dark red) from SVPS-36632. (B) SSS from SVPS 36632. The SSS values marked by light blue dots were flagged as invalid (due to air bubbles). The red arrows indicate manually removed freshening and saltening events that could not be validated with other data sets. (C) Quality-controlled SSS record from SVPS 36632 (blue) and SSS values measured by nearby drifters as shown in panel A. Note that several of the freshening events measured by SVPS 36632 were retained because they were confirmed by nearby drifters.

2014 passed the quality control.

This rather conservative approach to the manual QC procedure (more details can be found in Hormann et al., 2014) probably leads to unnecessary elimination of real freshening and saltening events, particularly when they are similar in amplitude to the variable noise level. However, the possibility of introducing substantial errors, for example, by air bubbles trapped in the conductivity cell, cannot be ruled out with our current knowledge. Future SVPS deployments by the GDP will use a revised SSS averaging algorithm that will account for the air bubble problem. Elimination of noise introduced by incorrect averages will then allow a revision of the QC procedure and may lead to reassessment of the previously determined SVPS salinity accuracy of the order of 0.02–0.04 psu (Reverdin et al., 2007a).

To investigate long-term drifter SSS bias, Argo profiles were selected that fell within one day of and 50–100 km distance from the drifter observations. Also, weekly standard—non-SST corrected—Aquarius v3.0 SSS retrievals were interpolated in space and time onto the corresponding seven-day mean positions of the individual drifters. The differences between the drifters and Argo or Aquarius SSSs indicate that the salinity sensor fitted on the drifters can provide reliable observations on the order of one year before exhibiting a noticeable drift that is probably caused by bio-fouling (Hormann et al., 2014).

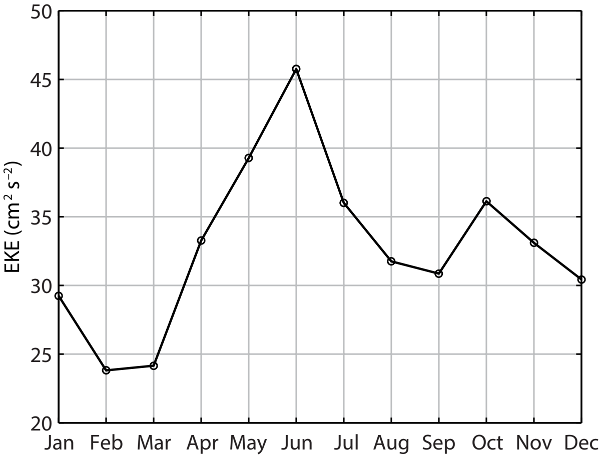

FIGURE 4. Geostrophic eddy kinetic energy (EKE) averaged over a 2° × 2° box centered on the nominal location of the SPURS mooring (24.5°N, 38°W) as computed from the unbiasing method that combines satellite altimetry, drifter, and wind reanalysis data described by Centurioni et al. (2008). The EKE values were computed from the AVISO altimetry data set and averaged for each month of the year to compute the seasonal cycle.

MESOSCALE EDDIES AND HORIZONTAL SALTWATER FLUXES

The geostrophic near-surface EKE of the tropical and subtropical North Atlantic is associated with the occurrence of mesoscale eddies and is characterized by a broad minimum region off the coast of West Africa between about 8 and 20°N and extending to approximately 50°W (Maximenko et al., 2009, their Figure 3). The EKE levels in the SPURS-1 region were computed with the unbiasing procedure described by Centurioni et al. (2008), which is based on a regression model between drifter data, including that from drifters deployed during SPURS, and the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO, Ssalto/Duacs delayed-time gridded updated products CRM:0020517) altimetry data set (Ducet et al., 2000). The EKE was computed on a 0.5° × 0.5° spatial grid for the entire SPURS-1 region and subsequently averaged over a 2° × 2° box centered on the nominal location of the SPURS-1 mooring (24.5°N, 38°W). The EKE values range from 20–50 cm^2 s^{-2} and show a well-defined seasonal cycle (Figure 4), with the maximum occurring in June, the minimum in February, and enhanced values from April through November.

Fluxes of salt in the presence of nonzero SSS gradients are associated with mesoscale eddies. Figure 4 therefore suggests that salt fluxes are expected to be larger in spring and summer. The divergence of the salt fluxes can be readily estimated from the drifters because the drifters concurrently measure mixed-layer salinity and velocity. Following the definition of the Lagrangian derivative (i.e., Gill, 1982), the derivative of the salinity following the drifter can be expanded as

$$\frac{DSSS}{Dt} = \frac{\partial SSS}{\partial t} + \vec{U}_{drifter} \cdot \nabla SSS \qquad (1)$$

where D/Dt is the rate of change along an individual drifter path, and $\vec{U}_{drifter}$ is the velocity of the drifter. For truly Lagrangian drifters, Equation 1 is an exact equation. We follow here the method described in Baturin and Niiler (1997). Using the Reynolds decomposition, we can write

$$\begin{gathered} SSS = \langle SSS \rangle + SSS' \\ \text{and} \\ \vec{U}_{drifter} = \langle \vec{U}_{drifter} \rangle + \vec{U}'_{drifter} \end{gathered} \qquad (2)$$

where $\langle\ \rangle$ denotes the ensemble average over a grid cell, and $'$ represents the deviation from that average. Substituting Equation 2 into Equation 1 and taking the ensemble average of Equation 1 over the chosen grid, by exploiting the fact that, by definition, $\langle SSS' \rangle = \langle \vec{U}'_{drifter} \rangle = 0$ and, if SSS is steady, $\frac{\partial \langle SSS \rangle}{\partial t} \sim 0$ (verifiable from Equation 3 below), we obtain

$$\begin{aligned} \left\langle \frac{DSSS}{Dt} \right\rangle &= \langle \vec{U}_{drifter} \rangle \cdot \nabla \langle SSS \rangle \\ &\quad + \langle \vec{U}'_{drifter} \cdot \nabla SSS' \rangle \end{aligned} \qquad (3)$$

Equation 3 shows that the rate of change of salinity along the drifter track is the sum of the divergence of the mean and eddy salt transports (or fluxes per unit area). The left-hand term of Equation 3 can be computed directly from drifter measurements, and the two right-hand terms can be computed from Aquarius retrieved SSS, while the mixed-layer eddy velocity $\vec{U}'$ can be computed from AVISO altimetry, and the mean near-surface velocity field $\vec{U}$ can be derived, for example, from the mean ocean topography (Maximenko et al., 2009) with added Ekman currents. Alternatively, the mean near-surface velocity field can be derived using the unbiasing technique described by Centurioni et al. (2008, 2009) and by adding the Ekman velocity back into the geostrophic field. The latter approach was used in this study.

Equation 3 was used here to diagnose the computation of the divergence of the mean and eddy salt fluxes in the SPURS-1 region from satellite products and to obtain insights on the relative magnitude of the mean and eddy terms. Assessing the possibility of deriving realistic salt fluxes from satellite products is important because such quantities contribute to the subtropical North Atlantic SSS budget. Thus, SSS and ocean currents measured from space can be a very powerful tool for helping to close the salinity budget of the SSS maximum region.

The comparison (Figure 5) of the drifter derived quantity $\frac{DSSS}{Dt}$ with the two terms on the right-hand side of Equation 3 was performed for monthly averages over a 1° × 1° box centered at 25°N, 38.5°W, which is approximately equivalent to the spatial resolution of Aquarius (i.e., slightly northwest of the SPURS-1 central mooring in order to accommodate the westward drift of the drifters). $\vec{U}$ and $\vec{U}'$ were computed using the unbiasing method of Centurioni et al. (2009) and AVISO sea level data, while S' and S are from Aquarius v3.0. Comparison of the three terms of Equation 3 shows that the divergence of the mean salt transport, that is, the first term on the right-hand side of the equation, is small compared to the eddy term, $\left\langle \vec{U}' \cdot \nabla SSS' \right\rangle$ (Figure 5). The sum of these two terms compares reasonably well with the Lagrangian time derivative of SSS. Note that the two sides of Equation 3 were computed from completely independent data sets, indicating that satellite and ocean-topography products may be of sufficient quality to estimate horizontal fluxes of salt within the mixed layer and over the entire SSS maximum region of the subtropical North Atlantic. Enhanced levels of salt flux divergences were indeed measured in spring and summer, when EKE is also large (Figure 4). The weekly temporal resolution of both satellite products is sufficient to resolve physical processes with periods longer than 14 days. The variance conserving spectrogram of the divergence of eddy salt transport shows peaks at 30, 80, and 250 days, a fact that does not point toward strong seasonality of the signal.

The diameter of mesoscale eddies in the SPURS-1 region is typically in excess of 200 km (Chelton et al., 2007). The AVISO gridded product is clearly adequate to resolve such spatial scales, but the gradients computed from Aquarius data produce a rather over-smoothed view of salt-transport divergence.

The good agreement of the divergence of eddy fluxes obtained from two independent data sets, although heavily averaged in time (one month) and space (1°), is encouraging and suggests that the Aquarius-derived SSS should be further exploited to estimate lateral advection processes outside of the SPURS region.

DISCUSSION AND FINAL REMARKS

A large number of SVPS drifters (88) and SVP drifters (56), representing NOAA's contribution to SPURS, and an additional 26 salinity drifters from the French Centre National d'Études Spatiales and the Spanish Institut de Ciències del Mar (ICM/CSIC) were deployed in the subtropical North Atlantic Ocean to measure the temporal and spatial evolution of SSS, quantify the contribution of the eddy field and the salinity variance to the lateral near-surface transport of salt in the mixed layer, and collect a data set to estimate the subgrid variability of SSS (i.e., within the Aquarius footprints) and evaluate the effect of such variability on Aquarius retrievals.

A flaw in the algorithm used for onboard computation of satellite-transmitted drifter salinities was found to be responsible for contaminating the data with spurious low-biased measurements, and, as a consequence, extensive manual editing of the salinity records was required. Our quality-control procedure resulted in 996,583 useful salinity measurements collected in the central SPURS-1 region between August 2012 and April 2014. The overall lifetime of the salinity sensors fitted to the SVPS drifters, taken as the time interval before a sensor exhibits a noticeable drift, was found to be on the order of one year (Hormann et al., 2014)—almost double previous estimates. The one-year estimate was based on direct comparisons between the drifters' SSS and the Aquarius v3.0 data set as well as occasional matches with data from Argo floats surfacing near the drifters. Future SVPS drifters of the GDP will carry a revised version of the algorithm to eliminate the noise problem.

During SPURS-1, the drifters, AVISO, and Aquarius concurrently measured

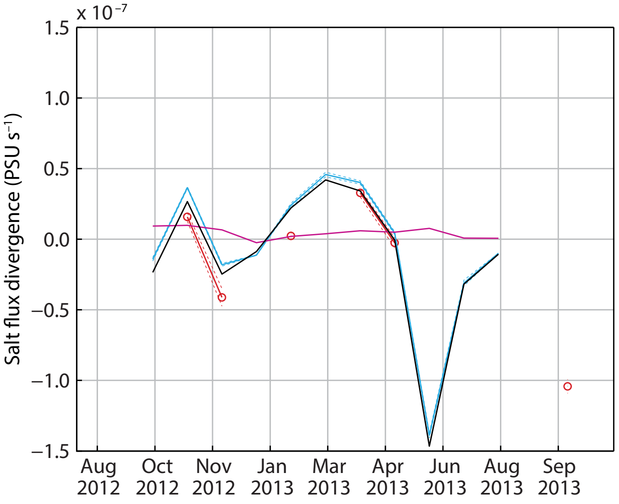

FIGURE 5. Lagrangian derivative of SSS from drifters (red, left-hand term of Equation 3), divergence of the mean salt flux (magenta, first right-hand term of Equation 3), divergence of the eddy salt flux (black, second right-hand term of Equation 3), and sum of the last two terms (cyan). The averaged time derivative of the drifter's SSS is shown only when more than 1,000 SSS observations were available in the box and within the 30-day period used for the temporal average.

salt flux divergence, and good agreement was found between the in situ and satellite data sets. The fluxes associated with the mean transport of salt were found to be small compared to the time-dependent contribution.

> “During SPURS-1, the drifters, AVISO, and Aquarius concurrently measured salt flux divergence, and good agreement was found between the in situ and satellite data sets.”

The salinity measurements from the large array of surface drifters presented in this paper permit validation of the Aquarius satellite retrieved salinity. The drifter salinity sensor measures in situ salinity where it is located at the time, while the Aquarius-retrieved salinity represents an averaged value over three relatively large footprints that are 76 km (along-track) by 94 km (cross track), 84 km × 120 km, and 96 km × 156 km.

The time mean (weekly) SSS variability estimated from the drifter data within the Aquarius footprints ranged from 0.083 to 0.093 (not shown). Work is underway to compute the representation error (also known as the sub-footprint variability) when the single-point in situ measurements, such as the ones derived from Argo floats, are used to validate the spatially averaged Aquarius salinity data (recent work of author Chao and colleagues). The salinity data collected by the SVPS drifters described in this paper therefore provide an opportunity to address this validation issue.

The drifter data suggest that as the Aquarius footprint increases from 50 km to 100 km and 150 km, the sub-footprint SSS variability shows a significant increase of 5% and 12%, respectively, and that such an increase can be related to lateral salt transport processes associated with fronts or filaments, or to freshwater input from precipitation as illustrated in Figure 3B. Currently, sub-footprint variability is not taken into account when performing global satellite validations using in situ measurements, but it can indeed be significant when the monthly Aquarius global mean accuracy is set for 0.2 psu. Its effect on SSS retrieval from Aquarius needs to be further evaluated, and it may, at times, pose a challenge to achieving nominal accuracy in the subtropical North Atlantic for parts of the year or under anomalous conditions.

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