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Evaluation of Drifter Salinities in the Subtropical North Atlantic

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ABSTRACT

Salinity measurements from drifters constitute an important in situ dataset for the calibration and validation of the sea surface salinity satellite missions. A total of 114 satellite-tracked salinity drifters were deployed within the framework of the first Salinity Processes in the Upper Ocean Regional Study (SPURS) experiment in the subtropical North Atlantic focusing on the period August 2012–April 2014. In this study, a subset of 83 drifters, which provided useful salinity measurements in the central SPURS region from a few weeks to more than one year, is evaluated and an ad hoc quality-control procedure based on previously published work and the new observations is described. It was found that the sampling algorithm of the drifters introduces a predominantly fresh bias in the noise level of the salinity data, probably caused by the presence of air bubbles within the measuring cell. Since such noise is difficult to eliminate using statistical methods, extensive editing was done manually instead. Such quality-control procedures cannot be routinely applied to the real-time data stream from the drifters. Therefore, a revision of the sampling algorithm of the drifter's salinity sensor is needed. Comparisons of the drifter's salinity measurements with independent datasets further indicate that the sensor can provide reliable observations for up to one year. Finally, little evidence was found that the quality of the drifter's salinity measurements depends on the presence of the drogue.

1. Introduction

The near-surface salinity distribution of the World Ocean is a key indicator of water exchange between the ocean and atmosphere, yet it is still poorly understood. Although the near-surface salinity generally reflects patterns of evaporation and precipitation, it is also affected by oceanic advection and mixing (e.g., [Schmitt 2008](#); [Yu 2011](#)). To improve our understanding of the processes modulating upper-ocean salinity, a first Salinity Processes in the Upper Ocean Regional Study (SPURS) was carried out in the evaporation regime of the subtropical North Atlantic where the salinity maximum water is formed (e.g., [Schmitt et al. 1989](#)). Because of typically low levels of precipitation, the small importance of mean advection, and a relatively weak mesoscale

eddy field, it was expected that near-surface salinity variance would be reduced in this region.

SPURS was designed to take place during the active times of the *Aquarius/Satellite de Aplicaciones Cientificas* (SAC)-D ([Lagerloef et al. 2008](#)) and Soil Moisture Ocean Salinity (SMOS; [Font et al. 2010](#)) sea surface salinity (SSS) satellite missions, which have been providing global SSS maps for a few years. The satellite retrievals are subject to large uncertainties and require in situ near-surface salinity data for their calibration and validation. Argo floats routinely measure subsurface salinity up to approximately 5 m below the surface (e.g., [Riser et al. 2008](#)), which necessitates knowledge of the near-surface haline stratification to extrapolate those observations to the surface (e.g., [Henocq et al. 2010](#); [Drucker and Riser 2014](#)). Measurements closer to the surface are available from recent Argo floats modified to measure salinity in the upper 5 m of the ocean ([Anderson and Riser 2014](#); [Riser et al. 2014](#), manuscript submitted to *Oceanography*) or from satellite-tracked drifters from the Global Drifter Program (GDP)

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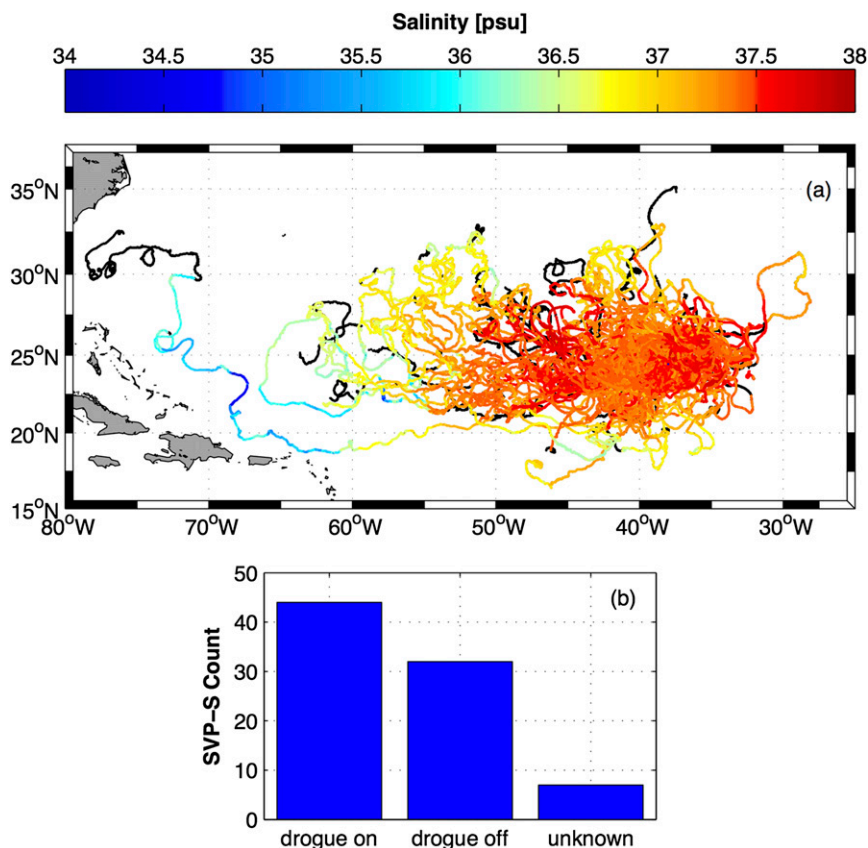


FIG. 1. (a) Tracks of SVP-S drifters in the SPURS region between August 2012 and April 2014, where color indicates quality-controlled salinity measurements; missing values are shown in black. (b) Drogue status of the salinity drifters as determined by a manual evaluation (i.e., visual inspection of the individual strain gauge data; cf. [section 2](#)).

and international partners equipped with a salinity sensor at an approximate depth of 50 cm (e.g., [Reverdin et al. 2007, 2014](#); Centurioni et al. 2014, manuscript submitted to *Oceanography*).

A total of 114 of such drifters were deployed in the SPURS region, focusing on the period August 2012–April 2014 (Centurioni et al. 2014, manuscript submitted to *Oceanography*). The goal of this study is to evaluate their performance and discuss the quality control of the salinity measurements. Several cluster deployments allow for intercomparisons of drifter salinities (Centurioni et al. 2014, manuscript submitted to *Oceanography*), particularly when other independent datasets such as Argo or *Aquarius* cannot provide useful observations. The quality control of the salinity measurements from the drifters is essential, since they represent an important dataset for the calibration and validation of the SSS satellite missions as well as can contribute to the closure of the salinity budget in the SPURS region ([Moisan and Niiler 1998](#); Schmitt and Blair 2014, manuscript submitted to *Oceanography*).

2. Data

In this study, we consider a subset of 83 (out of 114) satellite-tracked Surface Velocity Program salinity drifters (SVP-S). All SVP-S drifters were manufactured by Pacific Gyre Inc., and provided useful salinity measurements in the central SPURS region from a few weeks to more than one year ($\sim 50\%$ of which were still active at the end of the analyzed period; [Fig. 1a](#)). The SVP-S drifters were equipped with an unpumped Sea-Bird Electronics SBE37-SI [accuracy: 0.0003 S m^{-1} for conductivity ($\sim 0.003 \text{ psu}$) and 0.002°C for temperature] located just underneath the surface buoy at an approximate depth of 50 cm. The conductivity (or salinity) sensor was polled for instantaneous sampling once a minute for 5 min before each 30-min-interval satellite transmission. The five instantaneous salinity samples were then averaged and the value was transmitted. A more complete set of SVP-S specifications can be found in [Reverdin et al. \(2007\)](#).

The presence of the drogue was detected with a strain gauge that measures the deformation of the drifter's hull

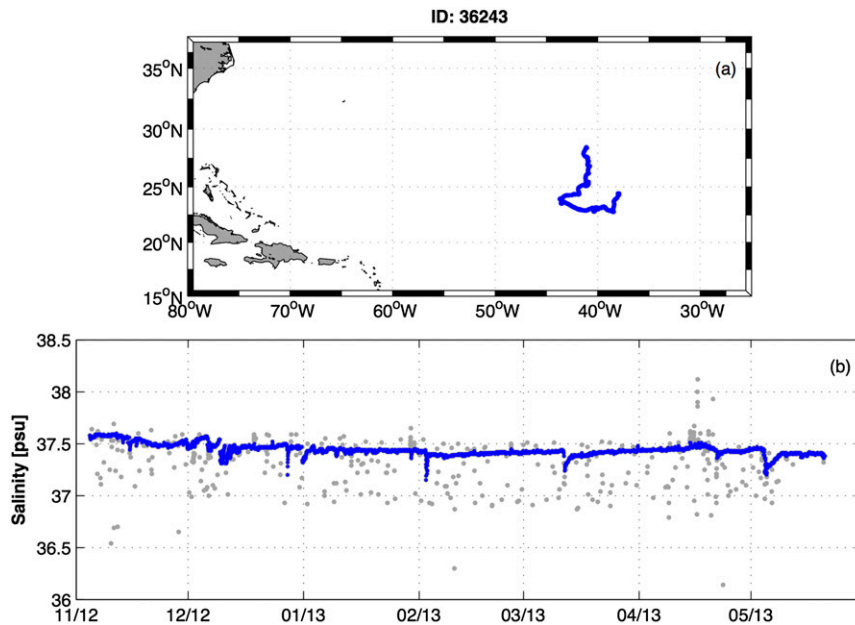


FIG. 2. (a) Track of SVP-S drifter 36243 deployed in the SPURS region at the beginning of November 2012, which had its drogue attached until the end of the record. (b) Corresponding time series of salinity measurements with (gray) and without (blue) data noise; note the noise bias predominantly toward fresher values.

due to the force applied by the tether-drogue assembly. A drogue-loss evaluation was performed on the SPURS salinity drifters, and we concluded that more than 50% of the drifters had their drogue attached through the end of the analyzed records (Fig. 1b).

To verify the drifter salinities, both delayed-mode and real-time Argo measurements in the upper 10 m (or dbar) with quality-control flags indicating good data (i.e., 1, 2, 5, or 8; Wong et al. 2014) were downloaded from http://www.usgoda.gov/cgi-bin/argo_select.pl. Typically, Argo floats collect one profile every 10 days. The salinity observations target a long-term accuracy of 0.01 psu (e.g., Riser et al. 2008).

We also use *Aquarius* level 3 SSS standard data, version 3.0, which are available as 7-day averages on a $1^\circ \times 1^\circ$ spatial grid (Lee et al. 2012; <ftp://podaac-ftp.jpl.nasa.gov/allData/aquarius/L3/mapped/V3/7day/SCI/>). Salinity measurements are taken at the L-band penetration depth of about 0.01 m, and the accuracy of monthly global maps is required to be better than 0.2 psu (Lagerloef et al. 2008).

The drifter salinities are additionally compared to 3-hourly precipitation rates from the Tropical Rainfall Measuring Mission (TRMM) 3B42 product, version 7 (Huffman et al. 2007; http://mirador.gsfc.nasa.gov/collections/TRMM_3B42_007.shtml), where the rainfall estimates are obtained by combining multiple independent microwave data and are available at a horizontal resolution of $0.25^\circ \times 0.25^\circ$.

3. Methodology and results

The averaging sampling mode of the SVP-S drifters introduces a predominantly fresh bias in the noise level of the salinity data. This bias was identified in the considered SPURS dataset by thorough inspection of all the time series and one example is given in Fig. 2. The continuous fresh bias, which is present year-round and not bound to the rainy fall–winter season (e.g., Yang et al. 2014, manuscript submitted to *Oceanography*), is probably caused by air bubbles that lower the conductivity of the water sample within the measuring cell. If one or more of the five salinity measurements used for computing the average is biased low by the presence of air bubbles, then the transmitted average is also affected. Further, the concentration of these bubbles may depend, for example, on sea state. This implies that filtering out the erroneous data with a statistical method that assumes a white-noise spectrum, such as the standard deviation criterion applied by Reverdin et al. (2014), may be hard to achieve. One of the main reasons is that the number of incorrect samples used for the average is not randomly distributed but may be related, for example, to environmental conditions such as strong wind and waves. Our approach to evaluate the SVP-S data was thus as follows:

- 1) We checked the transmitted positions for errors, and identified isolated salinity and temperature

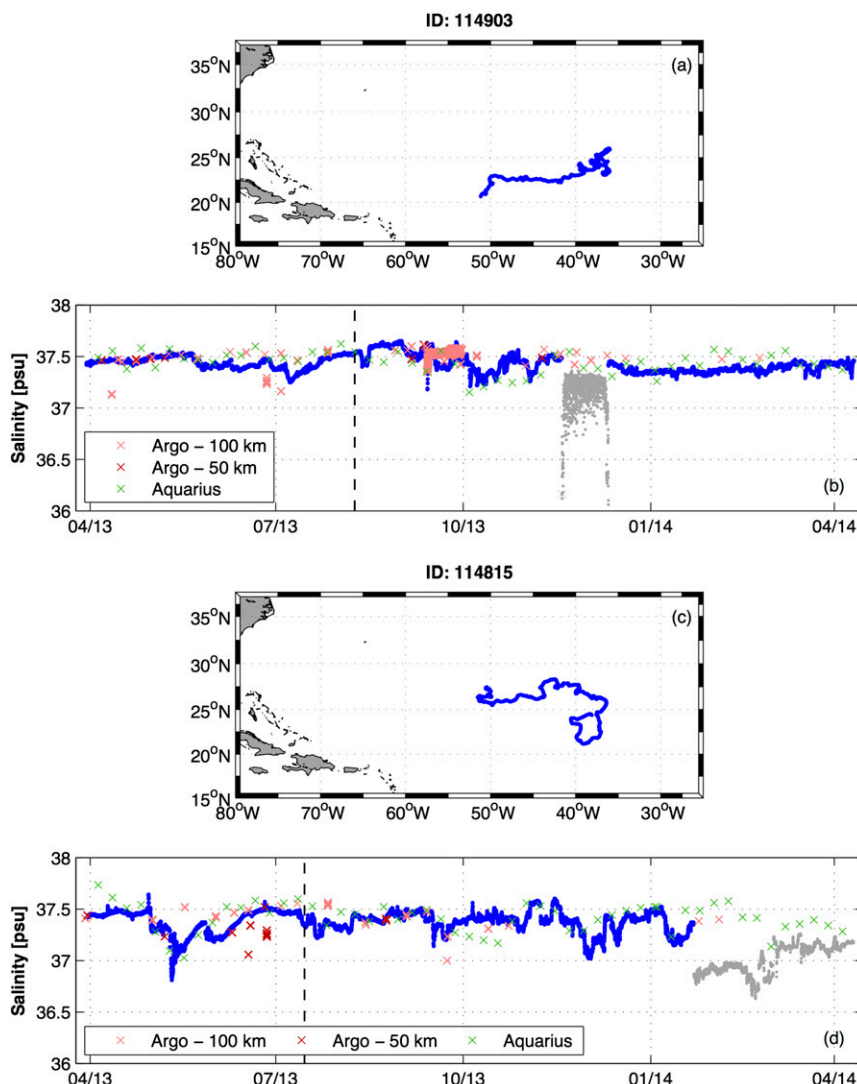


FIG. 3. (a) Track of SVP-S drifter 114903 deployed in the SPURS region at the end of March 2013. (b) Corresponding noise-removed (gray) and final (blue) time series of salinity measurements, with superimposed nearby Argo (100-km distance: light red, 50-km distance: red) and *Aquarius* (green) data (see text for Argo/*Aquarius* details); drogue loss is marked by the dashed line. (c),(d): As in (a),(b), but for SVP-S drifter 114815.

spikes as collected by the SBE37-SI sensor. Since the temperature measurements were also used in the onboard salinity computation, bad temperature data points were removed along with their corresponding salinity values (cf. [Reverdin et al. 2014](#)). This step eliminated about 2% of the data.

- 2) We performed a visual inspection of the individual salinity measurements to manually eliminate the data noise using a graphical polygon method. This removed an additional 4% of the data. An example of such noisy records is shown in [Fig. 2](#); note that besides the predominant bias toward fresher values

in the noise level, there is also indication of moderate random noise of the order of ± 0.1 psu.

- 3) The final step consisted of verifying the drifter salinities against independent datasets and inter-comparing the drifter salinities to discard/validate spikes, drifts, and sections of the data records that exhibit temporary steplike offsets as described by [Reverdin et al. \(2014\)](#). Such offsets may be attributed to foreign objects within the measuring cell, a malfunction of the sensor's electronics or physical features like eddies, fronts, and filaments. These qualitative comparisons eliminated less than 2% of

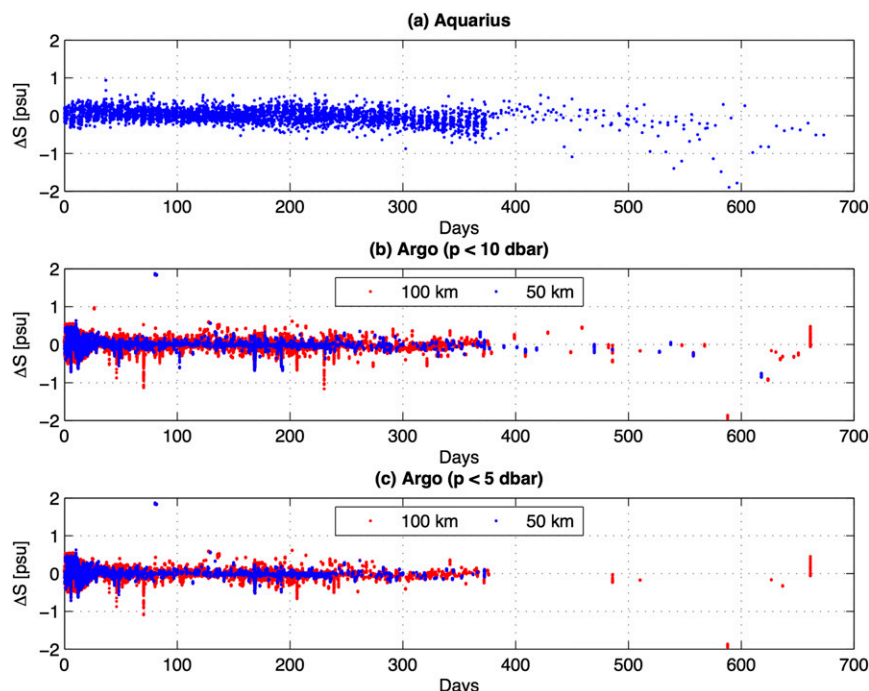


FIG. 4. Salinity differences between the SVP-S drifters and (a) *Aquarius* data (blue), and Argo measurements (100-km distance: red, 50-km distance: blue) in the upper (b) 10 and (c) 5 dbar (see text for Argo/*Aquarius* details).

the remaining salinity data and more details are given below.

Similarly to [Reverdin et al. \(2014\)](#), Argo profiles were selected within 1 day and both 50- and 100-km distances of each drifter measurement while the weekly *Aquarius* data were mapped onto corresponding 7-day mean positions of the individual drifters using a Delaunay triangulation interpolation method. The comparisons between these independent datasets and the noise-removed drifter salinities revealed a few more suspicious data points that were additionally eliminated. Two examples are illustrated in [Fig. 3](#), which shows intermittent erroneous observations typically caused by foreign objects within the measuring cell followed by a recovery ([Figs. 3a,b](#)) and a final failure of a sensor ([Figs. 3c,d](#)). In contrast to [Reverdin et al. \(2014\)](#), we did not attempt to adjust such salinity measurements to avoid introducing artificial errors deriving from a rather large natural near-surface salinity variability due to eddies, fronts, and filaments, which can be in excess of 0.1 psu ([Centurioni et al. 2014](#), manuscript submitted to *Oceanography*).

Previous studies on the evaluation of SVP-S data pointed out that the salinity sensor drifts over time, where small drifts were usually observed during the first 6 months (e.g., [Reverdin et al. 2007, 2014](#)). To estimate

the drift of our salinity sensors, we compared the quality-controlled drifter salinities with the nearby Argo (i.e., within 1 day and both 50- and 100-km distances of each drifter measurement) and track-projected *Aquarius* data. The comparison with *Aquarius* SSS data indicates that a sensor drift could occur after approximately 10–12 months ([Fig. 4](#)). Because of the known temporal instability of *Aquarius* ([Lagerloef et al. 2013](#)) and the lack of evidence from the comparison with Argo data, the drifter salinities were not adjusted. Argo measurements in the upper 10 m show no detectable drift beyond the level of the variance associated with ocean physics and haline stratification effects; note that the comparison leads to very similar conclusions when using Argo data in the upper 5 m only ([Figs. 4b,c](#)).

The comparison between drifter and *Aquarius* salinities further confirms that the latter is affected by seasonal biases (cf. [Hernandez et al. 2015](#)), with drifter salinities commonly higher/lower during boreal fall/spring ([Figs. 5a,b](#)), thus reflecting the seasonal cycle of the SSS maximum in the subtropical North Atlantic (e.g., [Gordon and Giulivi 2014](#)). As discussed in [Reverdin et al. \(2014\)](#), drogue loss could have a bearing on the drifter's salinity data. We examined the dataset for the influence of drogue presence in terms of the salinity differences between the drifters and both Argo and *Aquarius* but found no clear correlation except perhaps for a slight

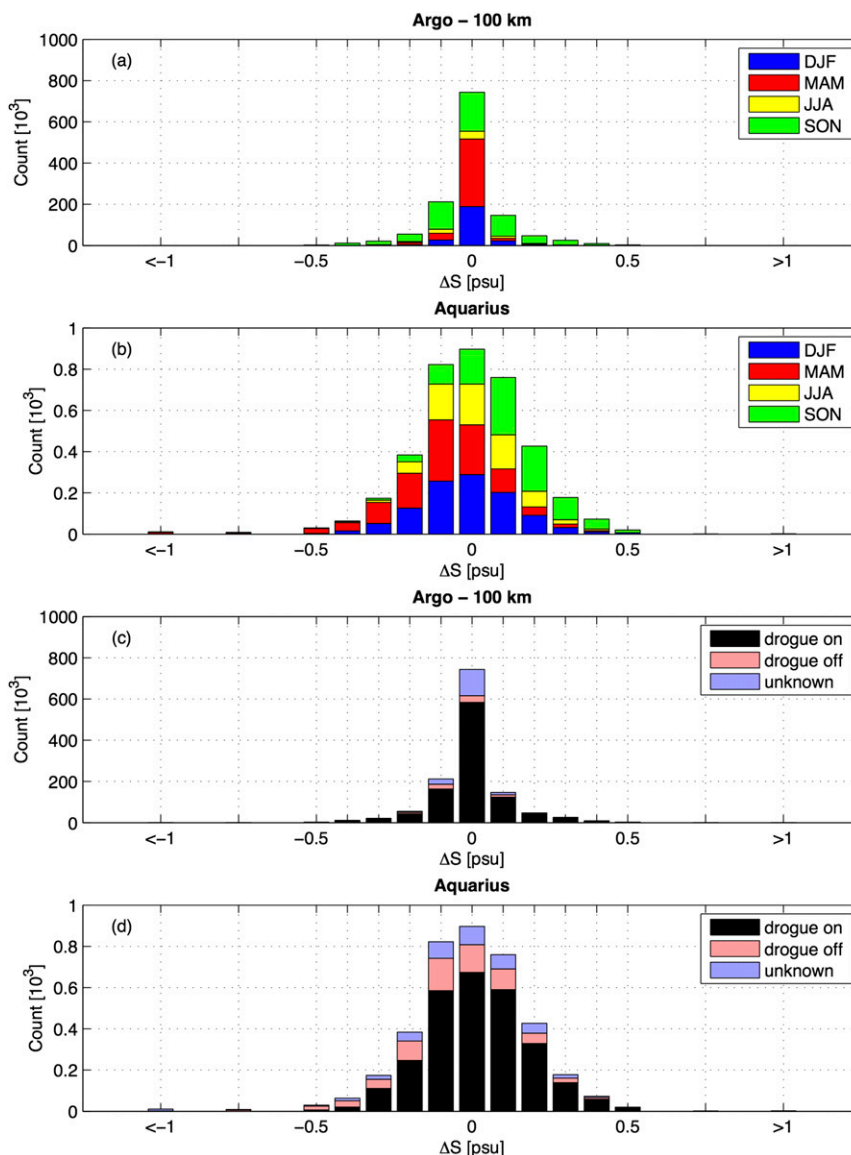


FIG. 5. Histograms of salinity differences between the SVP-S drifters and (a),(c) Argo–100 km, and (b),(d) *Aquarius* data (see text for Argo/*Aquarius* details) differentiated into (a),(b) seasons (December–February: blue, March–May: red, June–August: yellow, September–November: green) and (c),(d) drogue status (drogue on: black, drogue off: light red, unknown: light blue).

negative bias (Figs. 5c,d). That is, our SVP-S observations in the SPURS region generally suggest that the SBE37-SI sensor can provide reliable salinity data for up to one year.

Recently, salinity measurements from drifters have been shown to capture well the effect of precipitation on the ocean (e.g., Reverdin et al. 2012; Boutin et al. 2014). To verify if large drops in the observed salinities—particularly when not confirmed by Argo/*Aquarius* data or nearby drifters—may be related to rain events, we attempted to compare such freshwater spikes with TRMM

3B42 precipitation rates mapped onto the individual SVP-S tracks using a method similar to the *Aquarius* SSS retrievals. The TRMM 3B42 data have been found to generally lie within the uncertainty bounds of Passive Aquatic Listener results in the SPURS region (Yang et al. 2014, manuscript submitted to *Oceanography*), and Fig. 6 shows an example of a drifter comparison: Two clear matchups were found (i.e., in December 2012 and at the end of October 2012), but not all occurrences of SVP-S freshening could be verified by the precipitation rates. Since these comparisons were generally determined

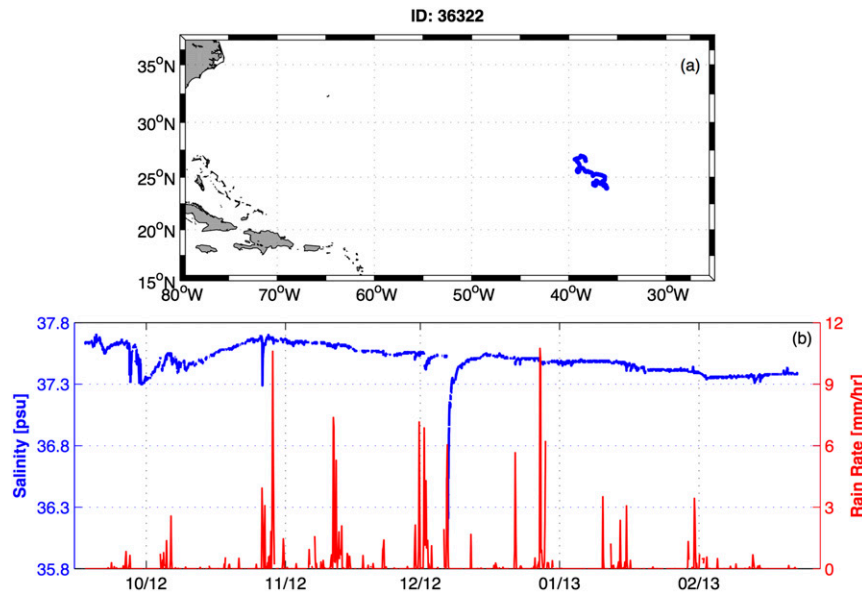


FIG. 6. (a) Track of SVP-S drifter 36322 deployed in the SPURS region during mid-September 2012, which had its drogue attached until the end of the record. (b) Corresponding time series of salinity measurements (blue) and TRMM 3B42 rain rate (see text for TRMM 3B42 details).

inconclusive (cf. Reverdin et al. 2012), we decided to retain the drifter salinities unless there were clear indications of a faulty sensor behavior as exemplified in Fig. 3. This decision was based on the spatiotemporal differences between the datasets and inherent uncertainties, as well as the large upper-ocean variability in the SPURS region on a variety of temporal and spatial scales (e.g., Busecke et al. 2014). We cannot rule out that some of the unverified freshwater spikes should have been discarded, but in most cases they were within the range of other observed occurrences that can be of the order of 0.9 psu in the SPURS region (Riser et al. 2014, manuscript submitted to *Oceanography*).

4. Conclusions

In this study, salinity measurements from SVP-S drifters deployed during SPURS in the subtropical North Atlantic were evaluated and quality-control procedures for such data were discussed. The main result of our study is that the sampling mode of the SVP-S drifters is responsible for the observed fresh bias in the noise level of the salinity data (cf. Fig. 2). Such bias is most likely caused by air bubbles within the measuring cell. These bubbles result in incorrect salinity samples entering the average computation used before data transmission via satellite. Since this sampling algorithm is a common SVP-S sensor configuration (cf. Reverdin et al. 2007), this finding not only had consequences for

our processing of the drifter salinities, requiring extensive manual data editing, but also may be of importance for other studies that use SVP-S drifters. The manual editing of erroneous salinity measurements was one of the few applicable solutions for the removal of the low-biased noise, but it presents two main disadvantages: First, it can be at times subjective and may lead to the elimination of valid signals such as the noticeable salty peak during mid-April 2013 in Fig. 2b, which although could not be verified by nearby Argo, *Aquarius* or drifter observations cannot be ruled out as real. Although such peaks were generally not verified against independent datasets, they typically showed a larger-than-usual noise level that becomes very apparent in an expanded view. The removal of such peaks represents a rather conservative approach that may oversmooth the near-surface salinity variance associated with ocean and air-sea interaction processes. Second, the manual editing procedure clearly cannot be routinely applied in the context of substantially expanding the use of salinity drifters within the GDP, mainly because the drifter data need to be made available in real time.

A revision of the SVP-S sampling algorithm is thus needed to enable the onboard filtering of incorrect salinity measurements. For example, checking the distribution of the sample population within each measuring cycle will allow for an automated quality control of the drifter salinities, similar to the one currently used to filter sea level pressure measurements from drifters. A

new generation of SVP-S drifters may also lead to an improvement of the previously determined accuracy of their salinity data (Reverdin et al. 2007, 2014).

Our study further indicates that the SBE37-SI sensor can provide reliable observations for up to one year, in contrast to previous estimates of about 6 months (Reverdin et al. 2007, 2014). Contrary to previous SVP-S studies (e.g., Reverdin et al. 2007, 2014), we did not attempt to adjust any salinity data to avoid introducing artificial errors possibly related to the rather large natural near-surface salinity variability of the subtropical North Atlantic (e.g., Busecke et al. 2014).

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Aquarius SSS data were obtained from the Physical Oceanography Distributed Active Archive Center at the NASA Jet Propulsion Laboratory, Pasadena, California. The TRMM 3B42 data used in this effort were acquired as part of the activities of NASA's Science Mission Directorate, and are archived and distributed by the Goddard Earth Sciences Data and Information Services Center.

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