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Temperature Measurements from Surface Drifters

G. REVERDIN,* J. BOUTIN,* N. MARTIN,* A. LOURENCO,* P. BOURUET-AUBERTOT,* A. LAVIN,+
J. MADER,# P. BLOUCH,@ J. ROLLAND,@ F. GAILLARD,& AND P. LAZURE**

* *L'OCEAN/IPSL, CNRS/UPMC, Paris, France*

+ *IEO, Santander, Spain*

AZTI, Brest, France

@ *CMM, CNRM, Brest, France*

& *LPO/IFREMER, Brest, France*

** *DYNECO/IFREMER, Brest, France*

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ABSTRACT

The accuracy of temperature measurements from drifters is first examined for 16 drifters (manufactured either by Metocean Data Systems or by Pacific Gyre) deployed with two temperature sensors in the tropical or North Atlantic Ocean. One of these sensors is the SST thermistor commonly used on Surface Velocity Program (SVP) drifters since the late 1980s; whereas the other sensor is a platinum temperature probe associated with a Seabird conductivity cell. The authors find (for 19 separate deployments) an average positive offset of the SST thermistor measurements in 17 out of 19 cases, exceeding 0.1°C in five instances. Among the five drifters that were at sea for a year or more, two present a large trend in this offset (0.10° and $-0.10^{\circ}\text{C yr}^{-1}$); and in two other cases, there is a clear annual cycle of the offset, suggesting a dependency on temperature. Offsets in 9 out of 12 drifters with sea time longer than 4 months present a negative trend, but the average trend is not significantly different from zero. The study also examined 29 drifters from four manufacturers equipped only with the usual SST thermistor, but for which either a precise initial temperature measurement was available or a float was attached to provide accurate temperature measurements (for a duration on the order of a month). These comparisons often identify SST biases at or soon after deployment. This initial bias is null (or slightly negative) for the set of Clearwater Instrumentation's drifters, it is very small for two out of three sets of Technocean drifters, and positive for the third one, as well as for the set of Pacific Gyre drifters (on the order of 0.05°C).

1. Introduction

The temperatures measured by surface drifters play a key role in the establishment of bulk sea surface temperature (SST) maps in blended products, as they are used to calibrate or validate satellite retrievals (Reynolds et al. 2007; O'Carroll et al. 2008). They also contribute a significant share of all in situ SST data in the last two decades (close to 40% of the data since 2000; Rayner et al. 2009). Compared to other in situ SST observations from ships, it appears that the drifter SSTs are colder, and this has been fairly steady since the early 1990s (Rayner et al. 2009). Rayner et al. (2003, 2006) suggested that this

could be the result of a cold bias of the drifter dataset. Alternatively, it could be that some of the biases in the other datasets have not been corrected. As this has an impact on long-term trends estimated from blended SST products, the quality and the nature of the biases of the temperatures measured from drifters need to be assessed. Comparisons in 2003 of buoy data with satellite retrievals of bulk SSTs suggested also a random error of 0.23 K on the buoy SSTs (both drifting and moored buoys; O'Carroll et al. 2008). Whether this is really an instrumental error or differences resulting from the match-up techniques (ocean submesoscales) needs also to be assessed. In this paper, we will discuss these issues from recent drifters deployed in 2005–09. The focus of this study will be on nighttime temperature, although we will also allude to the quality and representativeness of daytime temperatures from drifters.

Corresponding author address: G. Reverdin, L'OCEAN/IPSL, CNRS/UPMC, Case 100, 4 Pl. Jussieu, 75252 Paris CEDEX 05, France.
E-mail: gilles.reverdin@locean-ipsl.upmc.fr

Since the early 1990s, drifters initially developed for the Surface Velocity Program (SVP) of World Ocean Circulation Experiment (WOCE) Tropical Ocean and Global Atmosphere (TOGA) experiments provide most of drifter sea surface temperature data. Temperature is still measured for these drifters (referred to as SVP drifters) as initially presented in Sybrandy and Niiler's (1991) manual, although manufacturing of the drifters has been carried during that period primarily by four different manufacturers (Clearwater Instrumentations, Metocean Data Systems, Pacific Gyre, and Technocean). The common drifter design consists of a surface float of nearly 40-cm diameter connected with a tether to a drogue, often a 7-m-long holey sock attached to it 12 m below the surface (there is a smaller alternative model with 32-cm-diameter surface float, but not considered here). Temperature measurement is done by a thermistor potted inside a stainless steel cap with epoxy resin stycast. Most of the metal cap protrudes in water to the outside of the buoy close to its lower end. Based on visual inspection of several types of drifters both after deployment or during occasional later visits, the water line (if the drogue is present and sea is not rough) is close to the equator of the float or a little above it (the manual mentions 2.5 cm above it), so that the metal cap should usually be at a depth near 17–18 cm (in calm seas). We expect it to be different in rough seas, as the surface float plunges under the sea surface a notable part of the time. The temperature is reported with a variable resolution ranging between 0.05° and 0.16°C for the different SVP drifters we consider.

2. Datasets

a. Salinity SVP drifters

In the first part of the study, we will consider 16 drifters that, in addition to the thermistor of the SVP drifters, were equipped with deeper temperature and conductivity sensors from a modified version of the Seabird SBE37 Microcat (Reverdin et al. 2007). Thirteen of the 16 salinity drifters (referred to as SVP-S) were manufactured by Metocean Data Systems and three by Pacific Gyre. Three of the drifters were recovered and deployed a second time at least a few months later, in one case (72578) after having been refitted by the manufacturer. Therefore, we have 19 deployments to consider. The drifters were deployed either in the Bay of Biscay (11) in 2005–09, in the tropical Atlantic (5) in 2006–08, and in the North Atlantic (3) in 2008, and sampled waters in the 9°–31°C range. In total, 18 out of 19 deployments were from French research vessels.

The two temperatures are reported at the same time, although the sensors do not have the same response time

and correspond to averages done over specified times before the reported time. The recommendation is for averages over 15 min, but this is not always applied, in which case the resulting lag between the two sensors is corrected prior to comparison. The deeper temperature (T2) sensor (a platinum PT100) is located at a depth between 40 and 56 cm depending on the type of drifter, thus, within a layer for which we expect nighttime temperature to be well mixed most of the time (exceptions can occur during warm-air advection or under rainfall). To check that, we compared the daily cycles of SST and this deeper (noted T2) temperature for different classes of SST daily cycle range (by 0.25°C increments). For each class, we found that the average daily cycle of the two sensors follow each other within 0.01°C in the time range 0000–0600 (local time) LT (to within an average bias), suggesting that stratification in the top layer is rarely significant during that time range. We will therefore consider this upper layer unstratified for 0000–0600 LT and will use the comparisons for those times to quantify instrumental temperature biases.

Based on documentation from Seabird, the Seabird temperature sensor (T2) should remain accurate to within 0.01°C accuracy during its first year of deployment. We will assume in this paper that the T2 measurements are perfectly accurate and that comparisons of SST to T2 (averaging the differences SST–T2 over 0000–0600 LT each day) is indicative of the SST biases and its evolution in time.

b. SVP drifters

To increase statistics on initial SST offsets, we have examined SVP drifters (23 drifters) equipped only with the SST thermistor, which were either deployed in batches (of two to four units) from French research vessels in 2007–08 or were attached with a surface float equipped with a precise PT100 temperature sensor at a depth of either 28 cm (1 Surface float in 2007) or 17 cm (5 Surplus floats in 2008; the Surface and Surplus floats are small floats, homemade at LOCEAN for the study of near surface processes; Reverdin et al. 2007).

For the 23 drifters deployed in batches (8 drifters from the R/V *Côtes de la Manche* in 2007 and 15 drifters from the R/V *Pourquoi Pas?* in 2008), there are a few nights when drifters deployed simultaneously are close enough so that average differences between their respective SSTs are expected to report primarily relative biases. We also compare the ship intake temperature measurement (calibrated temperature probe located a few tens of a centimeter within a good water flow taken at the bowhead or along the side of the ship) at the time of deployment to the first drifter SST measurement. Because of time variability and insufficient resolution of

TABLE 1. Histogram of the number of drifters (out of 18) by classes of offsets (one drifter with 0.44°C average offset was not retained). The first line is the initial (15 days) offset; the second line is the average offset.

Offset (°C)	−0.045	−0.015	0.015	0.045	0.075	0.105	0.135	0.165
No. of drifters	0	2	4	7	3	1	1	
No. of drifters	0	2	4	7	2	2	1	

the reported drifter temperature, this individual comparison has a large uncertainty. To reduce this uncertainty, we will average initial differences over sets of drifters.

SVP drifters attached with Surfact or Surplis floats provide time series of SST offsets (by late night comparison) in a similar way to what is done with SVP-S drifters. The length of the investigated period is, however, too short to estimate a drift in the SST offsets, and these comparisons will only be used to estimate “initial” offsets. The Surfact and Surplis floats are much smaller than the SVP drifter (cf. the Surfact design in Reverdin et al. 2007), are designed to follow the surface of the sea, and are attached with a 4–8-m-thin tether to the SVP drifter. They were recovered and either post-calibrated (the five Surplis attached to Technocean SVP drifters in 2009) or compared to another calibrated drifter in a later deployment (the Surfact attached to a SVP/wind observation through ambient noise (wotan) Metocean drifter in 2007). These comparisons indicate that their temperature measurements remain to within a 0.01°C accuracy during their operating life time of less than 50 days.

3. SST offsets

a. SVP-S drifters

We will estimate SST offsets as the nighttime (0000–0600 LT) average of $DT = SST - T_2$ for each night. Then, these offsets are averaged over 15 successive nights to minimize noise related to discrete sampling, and to the resolution of reported SSTs, which is particularly poor for the first five drifters (0.16°C). The linear trend is estimated by regression of these 15-day averages. The average DTs (as well as the initial 15-day DT) are reported as histograms in Table 1 for the 19 deployments. The average offset value varies from close to zero for two drifters, to slightly over 0.1°C for four drifters, and a very large 0.44°C for one drifter. As the frequency of biases as large as this last one cannot be assessed from this small dataset, we will not retain it in the following statistics. Although this drifter would not

have been identified as biased with the criteria applied to the set used in O’Carroll et al. (2008), we expect that careful comparisons with other datasets could be used to identify this drifter as having dubious temperature. The distribution of the 18 other values is not distinguishable from a Gaussian with median 0.055°C and average 0.059°C (a standard deviation larger than 0.03°C, with extrema at −0.003° and 0.139°C, and an rms uncertainty on the average of 0.007°C).

Interestingly, for the two drifters that were redeployed after close to half a year out of the water (and a refit in one case), the biases are noticeably different for the second deployment. For Metocean drifter 72578, the difference exceeds 0.1°C (biases for first and second deployments of 0.037° and 0.139°C, respectively). For this drifter, comparisons upon deployment (intake temperature of the R/V *Cotes de la Manche*) indicate no changes in the T2 sensor, so that most of the difference is indeed from the SST measurement. There was also little trend in DT during each of the deployments and therefore the change happened in between (recovery, transport, storage, or deployment). For Metocean drifter 52197, there was a larger trend in DT (toward less positive values), so that the evolution between deployments is not so different from the trends observed at sea. Thus, the differences between the average biases of the two deployments (0.075° and 0.023°C, respectively) could be the result of a linear trend in time; note also that this drifter was sent to the manufacturer for refitting the batteries between the two deployments.

The largest differences between beginning and end of drifter’s life related to the linear trend are on the order of 0.102°C and −0.041°C (0.104°C and −0.105°C normalized over a year, respectively). In many cases, the linear trend explains a good part of the variability in DT, but in some cases, this is less so, with indication of a sensitivity of the offset to temperature. To illustrate the first situation, the daily (and 15-day averaged) bias estimates are plotted for two drifters that have a lifetime spanning roughly 1 year (Fig. 1). As final and initial temperatures are close, this linear trend cannot be related to a dependency in temperature, but it might be related to aging of the thermistor, circuitry, or its electronics. On these two plots (Fig. 1), there are, however, also deviations from the linear trend that could be related to temperature (larger offsets for low T on the upper plot, and lower values for low T on the lower plot). This dependency of the offset on temperature is also evident on other drifters, which do not present clear long-term trends. This can be witnessed on the scatterplot of DT versus T (averaged over 15 days) for two drifters spanning 9 and 14 months, respectively (Fig. 2). This (weak) dependency on temperature could be related to the

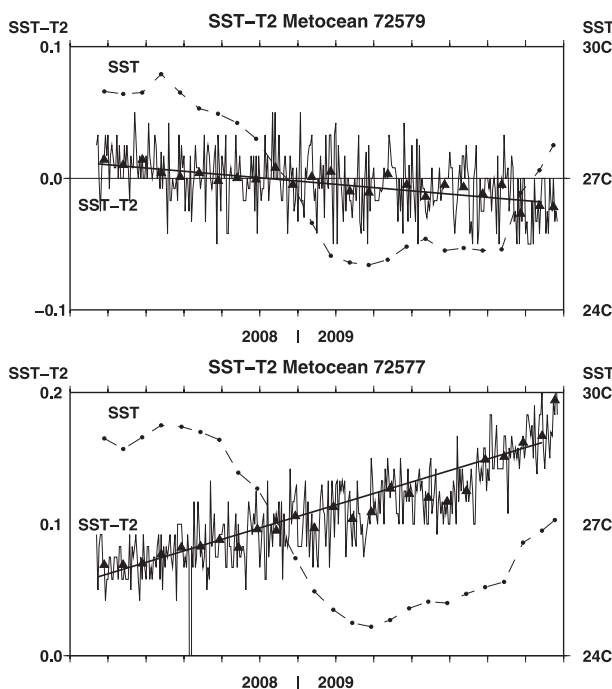


FIG. 1. Time series of nighttime (0000–0600 LT) SST-T2 (continuous line) with triangles for 15-day averages, and the linear trend is also plotted. The dashed line is the SST (also averaged by 15 days). The two drifters each had a sea life on the order of 12 months (ticks on horizontal axis every month).

calibration of the thermistors (done at three points: 0°, 25°, and 37°C) or to an electronics dependence on temperature. It remains within a 0.04°C range for the seven drifters examined, which are long-enough lived, such that the temperature dependency can be separated from a related trend related to aging.

In Table 2, we provide a histogram of the trends either over lifetime or normalized over a year of the 12 SVPS drifters that lived more than 150 days (5 out of those 12 lived a year or more). For all these drifters, the uncertainty on the trend estimate is smaller than 0.015°C yr⁻¹. The statistics are not robust, and suggest a non-Gaussian distribution, with seven values between -0.02 and +0.02, but extreme (absolute) values larger than 0.10°C (when normalized over a year), so that we do not have a representative distribution because of the small number of realizations. In 9 out of 12 cases, the bias is negative, but the average value is nonetheless small, -0.006°C yr⁻¹ (when averaging the annually normalized values) or 0.02°C over the lifetime of the drifters. Notice also that because 7 out of the 12 drifters also present an average trend of more than 1°C in the temperature measured over the life cycle, it is possible that part of the estimated trend in DT is related to the dependency on temperature discussed previously and not to aging.

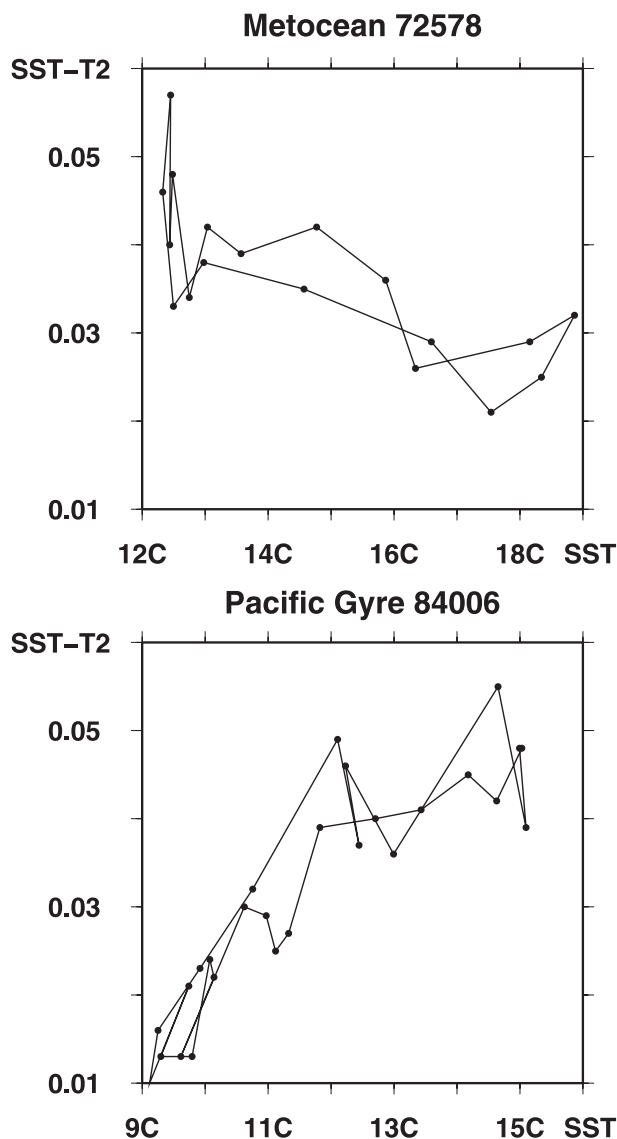


FIG. 2. Time series of DT as a function of T [for 15-day averages of nighttime (0000–0600 LT values)] for two drifters of close to 9 months (72578) and close to 14 months (84006) duration.

b. SVP drifters

During batch deployments, drifters were deployed within 1 km of each other, and we checked from the research vessel TSG salinity that there was no frontal structure initially in the batch. The SSTs from different drifters in the batch deployments were compared for close-by pairs of drifters during successive nights when the drifters remain close together (within 4 km), and the absence of submesoscale structures is assumed based on 1) no resolved variability in the difference between the two drifters temperatures during the night and 2) simultaneous results for successive nights. This was done

TABLE 2. Histogram of the number of drifters (out of 12 with life span longer than 4 months) in classes of average trends over the life span (line 1) and over 1 year (line 2).

Avg trend (°C)	−0.14	−0.10	−0.06	−0.02	0.02	0.06	0.10	0.14
No. of drifters	0	0	3	7	1	0	1	
No. of drifters	1	0	2	7	1	0	1	

for eight Technocean drifters in three deployments in 2007, as well as for 15 drifters in five deployments in 2008. In one instance, the third deployment of 2007 (four drifters), two pairs of drifters separated quickly, with a very uncertain comparison between the two pairs, which we do not retain (uncertainty on the order of 0.05°C); whereas the relative difference within each pair is estimated with an uncertainty of 0.01°C or less by averaging the different night estimates. This small uncertainty is typical of most pairs, with the exception of one pair in 2008, where a small structure was probably crossed certain nights, although distance was small (on the order of 2 km), and for which the resulting uncertainty is larger (on the order of 0.02°C).

As the uncertainties are small, the distribution of these average differences provides an estimate on the scatter in offsets. Assuming that the distribution of offsets is Gaussian (variance σ^2), the distribution of the differences is also Gaussian (with variance $2\sigma^2$). In 2007, the (absolute) differences range from 0° to 0.060°C, inferring σ close to 0.02°C (but this is rather uncertain with only five independent pairs). In 2008, we find systematic differences between the different makes of drifters. Clearwater drifters average the lowest and are 0.027°C lower than Technocean drifters and 0.066°C lower than Pacific Gyre drifters (five drifters each). The distribution of the average differences is from 0° to 0.060°C in the pair Technocean–Clearwater, and it is from 0.040° to 0.083°C for the Pacific Gyre–Clearwater drifters. Assuming that the average differences are related to systematic “manufacture based” offsets that can be removed, these two distributions are also compatible with σ at most of 0.02°C. These estimates of σ are less than what we found in the examination of salinity drifters of section 2a (mostly Metocean drifters), where the 18 individual initial biases ranged over a 0.14°C range (implying a σ of 0.034°C).

We will also infer estimates of the absolute drifter SST offsets from comparisons with the ship’s intake temperature at the time of deployment. An offset in intake temperature was first removed. It was estimated by comparing the intake temperatures to late night conductivity–temperature–depth casts. For both cruises, we find that the intake temperature reads a little high by 0.01°–0.015°C (with an average of 0.013°C). The comparison of the drifter measurement with the corrected intake temperature

at a depth of 3–4 m can be fraught with errors, when the upper layer is stratified (mostly near midday) and because drifter measurements are reported up to an hour after deployment. This is the case for two deployments in 2007 and three in 2009, which will not be considered, whereas the other deployments were either in the late night/early morning or late afternoon/early night when the errors related to stratification or time evolution should be less. There is also the uncertainty related to the resolution of reported drifter SSTs (in most cases, 0.08°C, except for five Clearwater drifters in 2008 when it is 0.05°C). This uncertainty will be reduced by averaging different drifter initial temperatures.

For the mid-September 2007 deployments, we find (six Technocean drifters of first and third batches) a net average offset of 0.005°C (0.010°C, in parentheses, estimated uncertainty resulting from the resolution). There is the possibility that we could have erred slightly toward positive biases, as there could have been a remaining stratification at the time of the third deployment. In 2008, we find a net offset of −0.007°C (0.008°C) for the five Clearwater SVP drifters, +0.009°C (0.012°C) for the five SVP Technocean, and +0.040°C (0.012°C) for the five SVP Pacific Gyre drifters. The actual uncertainty on these averages is actually probably larger than what we report because of the uncertainty in the intake temperatures (which has an average correction) and because of the difference in time between intake and drifter temperature measurements. These offsets are compatible to within the estimated uncertainties with the result of the comparisons of the pairs of drifters after deployment. They indicate clear positive offsets in the Pacific Gyre SVP drifters but not in the other drifters. The results for the 2007 and 2008 Technocean drifters are compatible with a weakly positive or null bias in these drifter temperatures.

We also attached to six SVP drifters (one SVP/wotan Metocean in 2007 and five SVP Technocean drifters in 2009) a Surfact/Surplus float providing temperature measurements with absolute accuracy on the order of 0.01°C. The comparisons indicate in four out of the six cases a positive SST offset (Table 3), with little or no evolution throughout the (short) deployments. We find no bias for the Metocean drifter, which came as a surprise based on the experience with the salinity drifters presented in section 2a. We also found a positive bias for four out of five Technocean drifters. The average bias over the five Technocean drifters is positive at 0.045°C, whereas for deployments in previous years, no average offset was found. It appeared that the lowest SST offsets originate from two Technocean drifters purchased in 2007, which have offsets compatible with the comparisons made in 2007 and 2008, whereas the three others with larger

TABLE 3. Average SST offset from six SVP drifters (30316 is a Metocean SVP/wotan drifter attached to a Surfact float deployed in 2007; the other five are Technocean SVP drifters attached to Surplus floats deployed in 2009, 72974 and 80477 have been purchased earlier than the other three). For drifter 30316, the calibration of the attached Surfact is established only by comparison with a new calibrated float for a later deployment in April 2008.

Drifter	30316	72974	80477	86617	86618	86619
Offset ($^{\circ}\text{C}$)	0.002	0.024	0.000	0.058	0.048	0.029

biases were purchased in 2008. This could be indicative of a change from year-to-year in manufacturing the drifters thermistor/electronics, although no specific changes in the manufacturing of the Technocean drifters were reported.

4. Conclusions

We focused this study on nighttime temperature measurements and identified in a large number of instances for these recent drifters positive offsets in SST measurements, sometimes exceeding 0.1°C . We found, however, differences between drifters made by different manufacturers or possibly from different years or different types. There is also the case of a drifter where the offset changed considerably after a refit and later deployment. These differences suggest a possible role, either of the electronics/circuitry, on how the thermistors are calibrated, or in the data reporting. (Biases could arise from how the data are rounded up; we are aware of an earlier set of salinity drifters where rounding up was to the next upper digit, which, with a resolution of 0.10°C , resulted in a net positive bias of 0.05°C .) In 5 out of 18 salinity (SVPS) drifters, we found that the bias was above the targeted accuracy of 0.10°C (but no such large biases were found for the 29 drifters in other sets of SVP drifters).

For all the drifters considered, we never found (based on the assumption that the reference temperature to which this is compared has not drifted) a large negative offset in SST. As the SVP drifters or derived versions of those (like the salinity drifters) are known to contribute most of the drifter data, the indication of an average negative bias in drifter SST relative to other in situ temperature data collected on ships (Rayner et al. 2003, 2009) is puzzling. An issue we raise would be the evolution of the drifter SST offset due to aging. In 2 out of 18 salinity drifters, there was a fairly large evolution of the offset over 1 year. In the set we examined, the trend due to this aging is more commonly toward a decrease, but the average effect is not significantly different from zero. The salinity drifters investigated had usually a shorter life span than the current SVP drifters, which have a

lifetime usually exceeding 1 year. Thus, these comparisons might not be representative of the average SVP drifter.

Within fairly homogeneous sets of drifters (same make, manufacturer, etc.), the standard deviations of the offsets is on the order of 0.03°C or less. This is much less than the 0.23°C error reported in O'Carroll et al.'s (2008) investigation. As we said, our limited investigations suggested significant differences between drifters from different manufacturers or different makes. These differences were, however, only on the order of 0.06°C . We, however, also found a drifter with an average bias of 0.44°C (out of 48 drifters). This drifter was not retained in this investigation because it should be possible to detect it with conventional comparisons with other datasets [e.g., analyses of satellite data as in O'Carroll et al. (2008)]. However, data of a drifter with this temperature offset would typically not be flagged by the operational centers. Retaining data of such drifters would quickly increase the errors to the 0.23°C standard deviation reported in O'Carroll et al. (2008). This published result combined with our investigation could be suggestive that there might be two or three drifters out of 50 drifters with such high offsets (a larger rate than what we found in the limited subsets investigated). Reducing the percentage of drifters with large offsets would very strongly improve the overall accuracy of the SST drifter datasets. This could be done with postdeployment monitoring of the offsets of drifter temperatures relative to a set of nighttime bulk SST products, in particular originating from remote sensing (W. Emery 2010, personal communication). It would also be useful to more systematically check the accuracy of drifter temperatures prior to deployment or at deployment. This could be done with a small subset of drifters from each manufacturer each year in well thermostated baths (near room temperature) or by comparison of drifter temperatures with a reference temperature at the time of deployment during the intercomparison deployments done at least once a year. (We also recommend that the standard resolution of reported temperatures be at least 0.05°C , and that these deployments should not be done at times with a warm subsurface layer.)

We focused the comparisons on nighttime measurements, and for the set of salinity drifters used, we found no indication of a residual stratification exceeding 0.01°C between the depths of the SVP SST sensor (near 18 cm) and the deeper temperature sensor (near 50 cm). In some areas of the world experiencing large precipitations or strong nighttime surface cooling, the late-night temperature difference between the two depths might be larger. During daytime, it might be interesting to document better the depth (or layer) representative of the SST

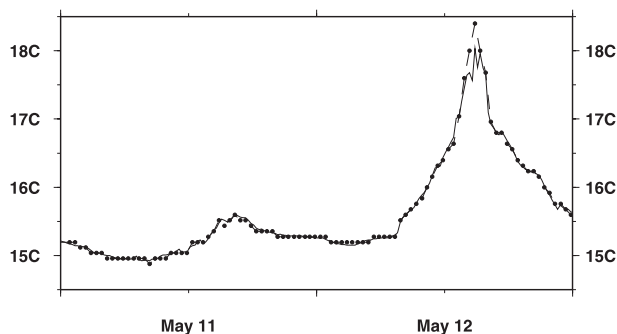


FIG. 3. Time series of corrected temperature (SST) from the Technocean 72974 (dots) and of the Surplus 27279 T2 measurement at 17 cm (solid line) on 11–12 May (notice higher SST than T2 in midday of 12 May).

temperature measurement from SVP drifters. Because we are so close to the surface, there is a large daily cycle in SST during some days with low wind, when we expect that daytime temperatures should usually be larger for SST than at the depth of T2 or even more than at the depth of ship intake measurements [averaging 8.4 m in 1997 for the voluntary observing ships (VOS) fleet, Kent and Taylor 2006]. For the 2009 SVP drifters that were attached to a float measuring temperature (T2) at 17 cm, we found that the daily evolution of SST from the SVP drifters was usually similar to T2 with occasional higher peak values. An example of excess SST over T2 value is given in Fig. 3 near midday of 12 May. Near this time for that day, two independent centimeter-resolution profiles obtained from a free profiler nearby indicated nearly 1°C temperature stratification in the top 20 cm. This suggests that the SST measured by an SVP drifter is more typical of the temperature in the top 20 cm than exactly at 18 cm, possibly because of relative flow with respect to the drifter.

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