Fulfilling Observing System Implementation Requirements with the Global Drifter Array

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ABSTRACT

The Global Ocean Observing System (GOOS) requirements for in situ surface temperature and velocity measurements call for observations at 5° × 5° resolution. A key component of the GOOS that measures these essential climate variables is the global array of surface drifters. In this study, statistical observing system sampling experiments are performed to evaluate how many drifters are required to achieve the GOOS requirements, both with and without the presence of a completed global tropical moored buoy array at 5°S–5°N. The statistics for these simulations are derived from the evolution of the actual global drifter array. It is concluded that drifters should be deployed within the near-equatorial band even though that band is also in principle covered by the tropical moored array, as the benefits of not doing so are marginal. It is also concluded that an optimal design half-life for the drifters is ~450 days, neglecting external sources of death, such as running aground or being picked up. Finally, it is concluded that comparing the drifter array size to the number of static 5° × 5° open-ocean bins is not an ideal performance indicator for system evaluation; a better performance indicator is the fraction of 5° × 5° open-ocean bins sampled, neglecting bins with high drifter death rates.

1. Introduction

The Global Ocean Observing System (GOOS), the ocean component of the Global Climate Observing System (WMO 2004), is composed of several components designed to observe various essential climate variables. Two of these variables are sea surface temperature (SST) and near–sea surface velocity (SSV). Goals for measuring these variables were first envisioned during scientific planning of the World Ocean Circulation Experiment (WOCE; WMO 1988), which sought global mapping of in situ SST and SSV measurements every 500 km × 500 km. WMO (1988, 2–22) noted that "there are roughly 1100 such useful resolution cells needed to map the world ocean." Assuming that a lifetime of 2.5 years could be achieved, WMO (1988) anticipated that 2200 satellite-tracked drifting buoys (drifters) would be required for global SST and SSV mapping over the 5-yr WOCE field program.

Goals for a *sustained* ocean observing system (in contrast to the 5-yr field program of WOCE) were defined at the International Conference on the Ocean Observing System for Climate meeting in St. Raphaël, France, in October 1999 (Needler et al. 1999). For in situ SST, crucial for bias correction of satellite observations and accurately determining temperature trends, the goal was to collect measurements at a temporal resolution of 25 observations per week, at a spatial resolution of 500 km (Needler et al. 1999) and to an accuracy of

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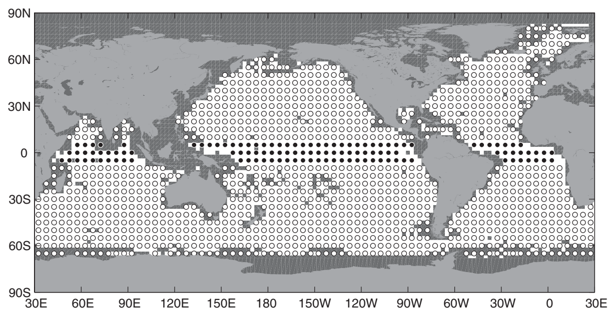

FIG. 1. Black and white dots show a regular array of 1250 buoys at a resolution of 5° × 5° covering the open ocean, from 65°S (globally) to 80°N (in the North Atlantic). The black dots are an array of 120 buoys that could be covered by a 5° × 5° array of moored buoys between 5°S and 5°N (WMO 2004). The 1130 white dots cover the remainder of the ocean surface. Dark gray shading indicates regions with a drifter death rate greater than $p = 0.1$ for $\Delta T = 30$ days (see Fig. 2); 1099 dots (979 white dots) are present in regions with a lower death rate.

0.2°–0.5°C. In situ measurements of SSV, needed for short-range (days to weeks) prediction and evaluation of seasonal to interannual ocean and climate forecast systems, were required at a temporal resolution of one observation per month at a comparable spatial resolution, at an accuracy of 2 cm s^{-1}, in order to resolve seasonal and time-mean currents to 10% of the eddy variability (Needler et al. 1999). The requirement for in situ SST observations has subsequently (Zhang et al. 2009) been refined to focus on reducing the potential bias in satellite-derived measurements below the Needler et al. (1999) upper threshold of 0.5°C. No analogous study has been conducted for SSV, and it is unknown how the recommended sampling impacts errors in satellite-derived surface currents or how accurately it resolves seasonal and lower-frequency circulation.

GOOS goals for these variables were further clarified GCOS-81 (UNESCO 2002), GCOS-82 (WMO 2003), and GCOS-92 (WMO 2004), which envisioned a 5° × 5° array of drifters and tropical moored buoys. GCOS-92 (WMO 2004, p. 63) noted that ‘‘global coverage. . .includes: enhancement of the surface drifter component to maintain coverage in each 5° × 5° region outside the near-equatorial band (achieved with approximately 1250 drifters if optimally deployed) [and] enhancement of the tropical moored buoy programme. . .(around 120 moorings in all).’’ As shown in Fig. 1, it is straightforward to estimate a 5° × 5° array of moored buoys between 5°S and 5°N that results in ~120 moorings (Fig. 1). However, it is likely that these 5° × 5° cells were also counted when reaching a goal of 1250 drifters for a global drifter array, as only ~1130 cells exist poleward of 5°N/S excluding marginal seas and ice-covered regions (Fig. 1).

The global drifter array is primarily supported by the U.S. National Oceanic and Atmospheric Administration (NOAA)'s Global Drifter Program (GDP), funded by the Climate Observation Division of NOAA's Climate Program Office. Drifter data are available online (NOAA 2015). A GDP drifter consists of a surface float attached by a tether to a holey-sock drogue (sea anchor) centered at 15-m depth (Niiler 2001; Lumpkin and Pazos 2007; Maximenko et al. 2014; Centurioni et al. 2015, manuscript submitted to *Bull. Amer. Meteor. Soc.*). The surface float includes alkaline batteries, a satellite modem, and a thermistor that measures subskin SST. Around 50%–60% of the global array includes barometers for sea level atmospheric pressure, an essential climate variable for the GOOS since GCOS-82 (WMO 2003). The drogue ensures that SSV can be derived from position changes with <1 cm s^{-1} impact from direct wind forcing in 10 m s^{-1} wind (Niiler et al. 1995), a requirement met by the modern ‘‘mini’’ SVP drifter assuming that the drogue remains attached (Lumpkin et al. 2013). Because a single drifter provides approximately hourly measurements of SST and location (Elipot and Lumpkin 2008; Elipot et al. 2016, manuscript submitted to *J. Geophys. Res. Oceans*), its presence in a 5° × 5° region will satisfy both SST and SSV temporal requirements for that region. The GDP relies on numerous national and international partners such, as the Office of Naval Research, to provide additional drifters meeting GDP instrument requirements and to provide deployment opportunities worldwide. Other important partners are meteorological agencies that use sea level atmospheric pressure observations from the drifters to improve numerical weather prediction (Centurioni et al. 2015, manuscript submitted to *Bull. Amer. Meteor. Soc.*) and to fund the addition of barometers to GDP-purchased drifters. These efforts are coordinated through the Data Buoy Cooperation Panel (DBCP) of the World Meteorological Organization and the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (UNESCO).

The global drifter array reached the GCOS-81 (UNESCO 2002) goal of 1250 drifters in September 2005, becoming the first completed component of the GOOS (Stanitski et al. 2005). Since then, this goal size has been used to assess the health of the global drifter array. However, it is important to note that drifters diverge from some regions of the ocean, converge in others, and transmit ocean data for a design half-life of ~450 days if they are not picked up or run aground (Lumpkin et al. 2012). As a consequence, meeting the goal of 5° × 5° observations of SST and SSV will not necessarily require 1250 drifters, although the simplicity of the 1250 goal has resulted in it being equated with $5^\circ \times 5^\circ$ sampling in program reports and status updates. No systematic study has yet been conducted to evaluate the number of drifters needed to satisfy $5^\circ \times 5^\circ$ sampling when they realistically move and die, and the impact of the absence or presence of a tropical moored array of buoys on this number.

In this study, observations of all drifters in the historical database are used to simulate the global drifter array under various lifetime assumptions, both with and without a completed array of tropical moored buoys. Observations from Volunteer Observation Ships (VOS) are not considered, but they may reduce the need for sampling along the major shipping lanes (e.g., Zhang et al. 2009). Because many actual drifters are deployed from these ships, it is shown that fewer observations are needed on these lanes in the simulations even without explicit inclusion of ship observations. Drifters are deployed in the simulations to guarantee $5^\circ \times 5^\circ$ open-ocean sampling. The number of drifters deployed per year and the steady-state size of the global array are determined as a function of lifetime. Emphasis is placed upon the instrument cost per year; no attempt is made to quantify deployment costs, which vary widely based on location and lead times. It is argued that the number of drifters needed per year to maintain $5^\circ \times 5^\circ$ open-ocean sampling, and the associated annual cost, is a more meaningful metric than the instantaneous array size. The spatial distribution of deployments needed in the simulations is compared to the actual deployment distribution, revealing where additional efforts and regional deployment partners are most needed.

2. Methodology

Since May 2005, the GDP has made 90-day forecasts of the global array (http://www.aoml.noaa.gov/phod/graphics/dacdata/forecast90d.gif). This was done as follows: First, the world was divided into an array of regular bins. Second, all drifters were identified that passed through each bin. Third, the locations of all these drifters were found at a time increment ΔT days later. Because some drifters will die due to technical reasons or because they were picked up or ran aground, the number after ΔT days will usually be smaller than the original number. Fourth, all the locations ΔT days later are used to calculate the binned probability distribution function (PDF) for a drifter in each bin. Finally, these PDFs for $\Delta T = 90$ days are accumulated for each drifter in the present configuration to calculate the odds of each bin containing at least one drifter 90 days in the future.

For 2005–14, these forecasts were done on a $5^\circ \times 5^\circ$ grid for $\Delta T = 90$ days using full matrices. More recently, Maximenko et al. (2012) and van Sebille et al. (2012) calculated the evolution of floating marine debris for shorter time steps ($\Delta T = 5$ days in Maximenko et al. 2012; 60 days in van Sebille et al. 2012) using this approach, but using sparse matrices (matrices with mostly zero elements) that permitted these calculations at higher resolution [$1/2^\circ \times 1/2^\circ$ and $1^\circ \times 1^\circ$ in Maximenko et al. (2012) and van Sebille et al. (2012), respectively]. van Sebille et al. (2012) also normalized the PDFs so that the tracer was conserved (i.e., the number of drifters after ΔT days remains the same as the original number) and included seasonal variations in the PDFs.

In this study, in order to simulate the global drifter array under various scenarios, PDFs are calculated for all drifters in the quality-controlled GDP database through March 2015, at $1^\circ \times 1^\circ$ resolution using sparse matrices, for $\Delta T = 30$ days. Both drogued and undrogued drifters are used, and all seasons are included, in order to increase the robustness of results in regions of sparse observations. Future refinements could include seasonal variations as in van Sebille et al. (2012); the results presented here should be interpreted as an average over all seasons.

Because the PDFs are not normalized to conserve the number of drifters from one time step to the next, simulated drifters will disappear from various bins with the same odds as determined by the actual observations. A map of the odds of dying in $\Delta T = 30$ days (Fig. 2, top) reveals "death zones," where drifters are more likely to run aground, be picked up, or fail (die) due to other external reasons (Lumpkin et al. 2012). The odds p of a drifter dying over an interval ΔT is nearly independent of the drifter's lifetime, suggesting that a reasonable model of the size of the drifter array N in the absence of deployments is $N = N_o \exp[-(pt/\Delta T)]$. This is consistent with a half-life $T_{\rm hl} = -\Delta T/p \ln(0.5)$.

A comparison of Figs. 1 and 2 reveals that a small but significant fraction of the $5^\circ \times 5^\circ$ open-ocean bins are located in regions where the death rate $p > 0.1$. These regions are indicated by dark gray shading in Fig. 1. An optimally designed observing system should rely on nondrifter platforms (such as moored buoys and VOSs) to sample SST and SSV in these bins, or should include frequent drifter deployments because drifters will die relatively quickly: $p > 0.1$ is consistent with a half-life < 200 days. Excluding these regions from the $5^\circ \times 5^\circ$ grid reduces the number of bins from 1250 to 1099. If the equatorial region between 5°S and 5°N is also excluded, then the number of bins is further reduced to 979.

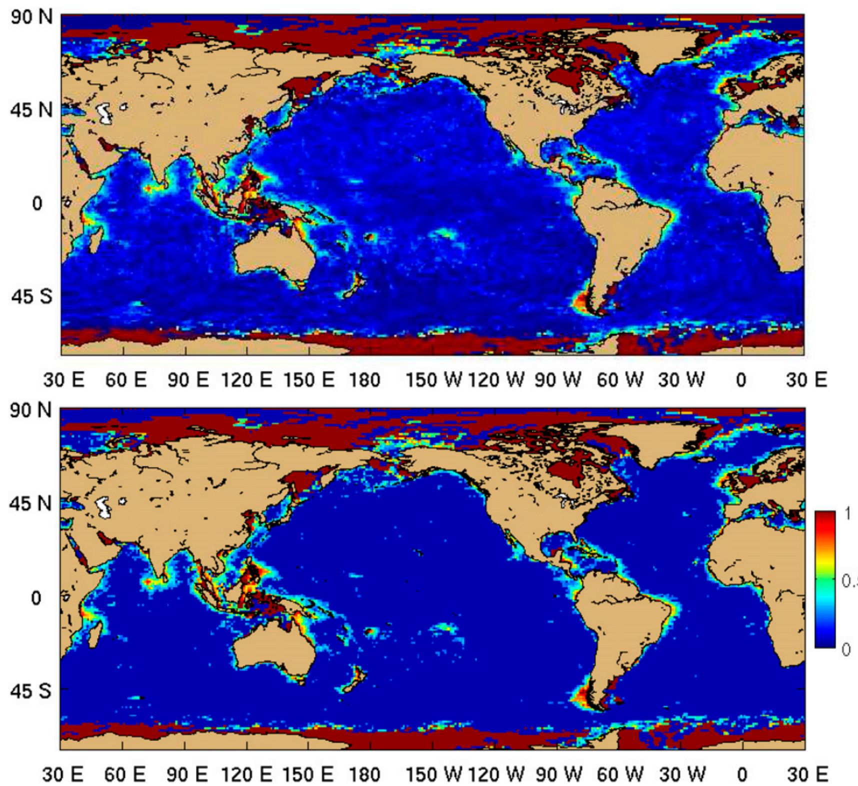

FIG. 2. (top) The odds of dying p in a time step of $\Delta T = 30$ days calculated from the actual drifter observations. (bottom) As in (top), but with all $p < 0.2$ replaced by $p = -(30\ \text{days})/(450\ \text{days}) \times \ln(0.5) = 0.0462$, consistent with a quit half-life of $T_{hl} = 450$ days.

In the ocean interior away from death zones (Fig. 2, top), the histogram of "odds of dying" for $\Delta T = 30$ days peaks at approximately $p = 0.05$, suggesting that the half-life for drifters avoiding death zones—that is, the death rate for quitting due to internal sources of failure (the "quit" half-life)—is around 380–460 days. This is close to the design goal of 450 days. The effect of this design goal can be examined in this study by replacing the background odds of dying with values consistent with quit half-lives of T_{hl} (e.g., Fig. 2, bottom). To implement this in the simulations, the PDFs of all bins with a nonadjusted death rate below $p = 0.2$ are rescaled so that $p = -\Delta T/T_{hl} \ln(0.5)$, where T_{hl} is the assumed quit half-life of the simulation.

All simulations are initiated with an array of 1250 drifters in a perfect, regular 5° × 5° grid in both the white and gray shaded areas shown in Fig. 1. Each drifter is projected forward in time by $\Delta T = 30$-day time steps, with the next bin chosen randomly (using the MATLAB function rand.m) according to the PDF for the origin bin. At each time step, all open-ocean regions away from death zones (Fig. 1) are evaluated to see if there is a gap greater than 5° between each bin center and the closest drifter. If so, a drifter is deployed in the center of the bin.

A suite of simulations are run for T_{hl} values ranging from 250 to 900 days in increments of 50 days (14 simulations), for two scenarios: "no tropical moorings," where the drifters must cover the entire white area in Fig. 1 with no gaps > 5°, and "with tropical moorings," where they must cover only the region seeded by the extratropical white dots in Fig. 1 without gaps > 5°. An example of a with-tropical-moorings simulation for $T_{hl} = 450$ days is shown in Fig. 3. The simulations are run for a total of 3600 days (~9.9 years).

Note that these simulations completely neglect the logistical challenges and associated costs of deploying drifters whenever a gap develops in the global drifter array. In practice, the GDP is not funded to charter vessels for deployments, relying instead on VOS traveling shipping lanes and on already-planned cruises for which the drifter deployments are a value-added side project. Planning these deployments requires months of lead time to take advantage of surface shipping, and no GOOS component is sufficiently funded to fill 5° gaps within 30 days anywhere in the world. These simulations also do not consider drogue loss, which often occurs before the drifter dies and

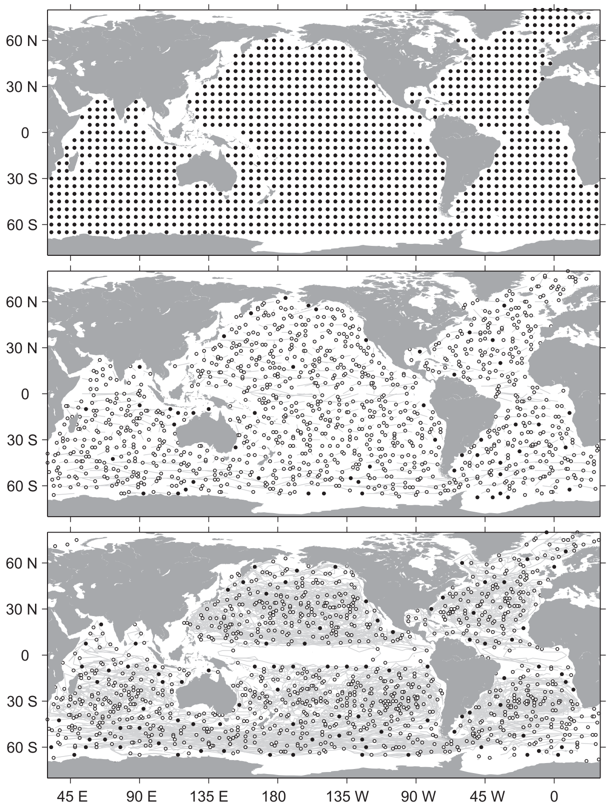

FIG. 3. Global drifter array simulation for $T_{hl} = 450$ days, shown at various time steps. This is a with-tropical-moorings simulation, for which no drifter observations are required in the near-equatorial band. (top) Before the first time step, the drifter array is a perfect 5° × 5° grid of 1250 drifters. (middle) After one step of 30 days, the existing drifters have moved (white dots with gray 30-day trajectories) or died, and gaps have opened in the array, requiring new drifters to be deployed (black dots). (bottom) The simulation after 3480 days.

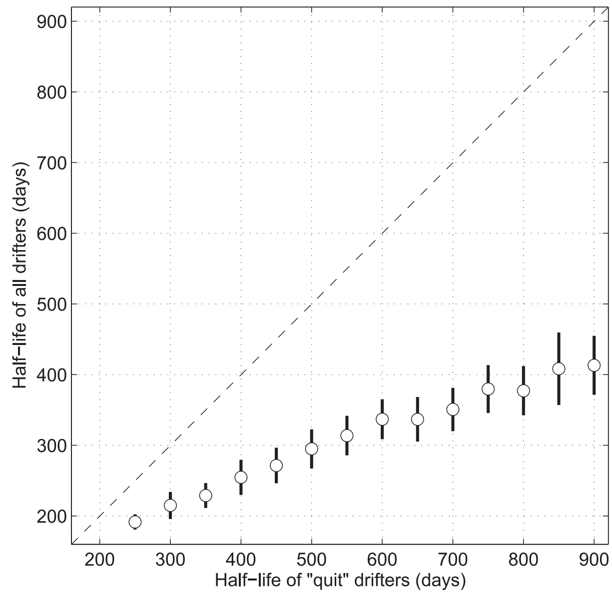

FIG. 4. Half-life of all drifters T_{all} in the simulations as a function of imposed "quit" half-life T_{hl}. Error bars indicate the standard deviation over the final 2 years of the simulation. Dashed line indicates $T_{all} = T_{hl}$.

negatively impacts the accuracy of SSV measurements. Finally, it should be noted that the statistics governing the simulated drifter motion are based on few drifters where the historical observational density is low (see Fig. 1 of Maximenko et al. 2014), and thus may underrepresent oceanic variability and the potential downstream fate of the simulated drifters in those regions.

3. Results

By construction, the simulations realistically evolve the simulated drifter array from one time step to the next. The drifters rapidly diverge from the near-equatorial band and from regions such as the Gulf of Guinea: within 90–120 days, in the absence of new deployments, pronounced gaps develop in the eastern tropical Pacific and Atlantic basins, across the near-equatorial Indian Ocean basin, and in the Gulf of Guinea. The drifters slowly converge toward the "garbage patch" centers of the subtropical gyres (e.g., Lumpkin et al. 2012; van Sebille et al. 2012), an accumulation that becomes obvious after the first year in simulations with $T_{hl} > 350$ days. Simulations with short quit half-lives quickly reach steady state as indicated by the number of drifters in the global array and the numbers dying/being deployed each time step, while those with long half-lives require many more iterations. For example, for $T_{hl} = 250$ days, steady state is reached within 180 days, while for $T_{hl} = 900$ days it is not reached until ~2220 days (~6 years). In simulations with large quit half-lives, many drifters accumulate in the centers of the subtropical gyres. In contrast, short T_{hl} simulations require more deployments per year but result in a more spatially homogeneous array consisting of fewer drifters.

In the remainder of this section, results are given for the various simulations averaged over the final 2 years of each simulation. In all cases, the simulations have reached a steady-state situation in this period.

a. *Drifter lifetimes*

The half-life of all drifters in the simulation (as opposed to the background "quit" half-life T_{hl}) can be estimated from the fraction p_{all} (including drifters in the death zones) that disappear each time step $\Delta T = 30$ days as $T_{all} = -\Delta T/p_{all}\ \ln(0.5)$ (Fig. 4). Values are nearly identical for the with-tropical-moorings and no-tropical-moorings simulations. Because the half-life of all drifters includes drifters in death zones (Fig. 2), it is shorter than the prescribed T_{hl} in all cases. This overall half-life increases approximately linearly from 192 ± 11 days for T_{hl} = 250 days to 337 ± 28 days for T_{hl} = 600 days. It increases more slowly for $T_{hl} > 600$ days and is not significantly larger at T_{hl} = 850 days. Regardless of how robustly the drifters are engineered, a subset of the array will run aground, be picked up, etc., at each time step. Thus, the results shown in Fig. 4 suggest that engineering the drifters to live longer than T_{hl} = 600 days is not cost effective for maintaining 5° × 5° coverage, although more reserve power is invaluable for permitting additional sensors.

b. Requirements to meet observing system goals

Figure 5 (top) shows the number of drifter deployments needed per year as a function of the ''quit'' half-life T_{hl}, which in the steady-state limit of the half-lives considered in this study is also the number dying per year. Black dots indicate the no-tropical-moorings simulations, while gray bullets indicate the with-tropical-moorings simulations. Error bars indicate the standard deviation of these values in the final 2 years of the simulations. As the quit half-life increases, the number of drifters needed per year decreases from ~1500 to ~1200 deployments per year for T_{hl} = 250–500 days, indicating the value of an increased goal lifetime (both to purchase drifters and implicitly to deploy them). However, the number needed per year tends to plateau for larger T_{hl}, and it is not significantly different for T_{hl} = 500–950 days with values of ~1000 deployments per year. Approximately 115–125 more drifters per year are needed in the no-tropical-moorings simulations than in the with-tropical-moorings simulations, a value smaller than the standard deviation (Fig. 5, top). The associated annual purchasing costs can be estimated as the cost per unit, $1800 at the present goal lifetime of 450 days, multiplied by the annual rate suggested from Fig. 5 (top) (i.e., 1000 deployments per year = $1.8 million per year). It is not clear if the cost per unit would increase significantly with increased goal lifetime; in the recent past, lifetime increases have been achieved via changes that did not impact unit price (e.g., battery manufacturer, data transmission algorithms). Depending on the satellite system being used, a larger array may also reflect greater transmission costs.

Because long-lived drifters will accumulate in the centers of the subtropical gyres, a larger global drifter array is needed to satisfy 5° × 5° sampling with larger T_{hl} (Fig. 5, bottom). A larger array is also needed if the global moored tropical array is not included. Clearly, the 1250 goal set in GCOS-81 (UNESCO 2002) is rather arbitrary, as it does not take into account the fact that drifters move. Based on the results found here, maintaining an array of 1250 drifters with 5° × 5° sampling corresponds to T_{hl} ~400 days in the no-tropical-moorings simulations and T_{hl} ~500 days in the with-tropical-moorings simulations.

c. Simulated versus actual deployment distributions

Figure 6 (top) shows the distribution of deployments per year needed to maintain 5° × 5° sampling in the no-tropical-moorings simulation with T_{hl} = 450 days. The distribution in the with-tropical-moorings simulation (not shown) is similar, except that the maximum along the equator is split into off-equatorial maxima straddling the near-equatorial band of the tropical moored array. Outside of this region, deployments are needed at the northern and southern edges of the domain, particularly at the southern edge, which has more ocean to cover and has fewer death zones. Deployments are also needed off the coasts of Costa Rica, Ecuador, and Peru in the eastern Pacific, off the western coasts of Africa in the eastern Atlantic, in the northwestern Indian Ocean (Arabian Sea), and in the northern and northwestern Pacific Ocean off the eastern coasts of Japan and Russia.

The distribution of actual deployments in the period 2006–14, scaled to be deployments per year, is shown in Fig. 6 (middle). On average, 1189 drifters were deployed globally per year during this period. Maxima indicate the locations of cruises servicing the TAO array in the tropical Pacific; shipping lanes between North America and Cape Town, South Africa; resupply and research efforts in the Drake Passage; research efforts in Asian marginal seas, the subtropical and subpolar North Atlantic, the southern Indian Ocean, and east of Puerto Rico; regional deployments by partners in Brazil, Australia, and New Zealand; and opportunistic deployments close to the Scripps Institution of Oceanography (La Jolla, California), NOAA/AOML (Miami, Florida), and Woods Hole Oceanographic Institution (Woods Hole, Massachusetts).

The difference between simulated and actual deployments (Fig. 6, bottom) indicates where more or fewer deployments are needed to maintain the desired 5° × 5° sampling of the global drifter array. The patchy distribution of positive and negative values along the equatorial Pacific reflects the logistical reality of TAO servicing cruises at specific longitudes. Negative values are found along the major shipping lanes, where VOSs are used to deploy many drifters in the real ocean, and

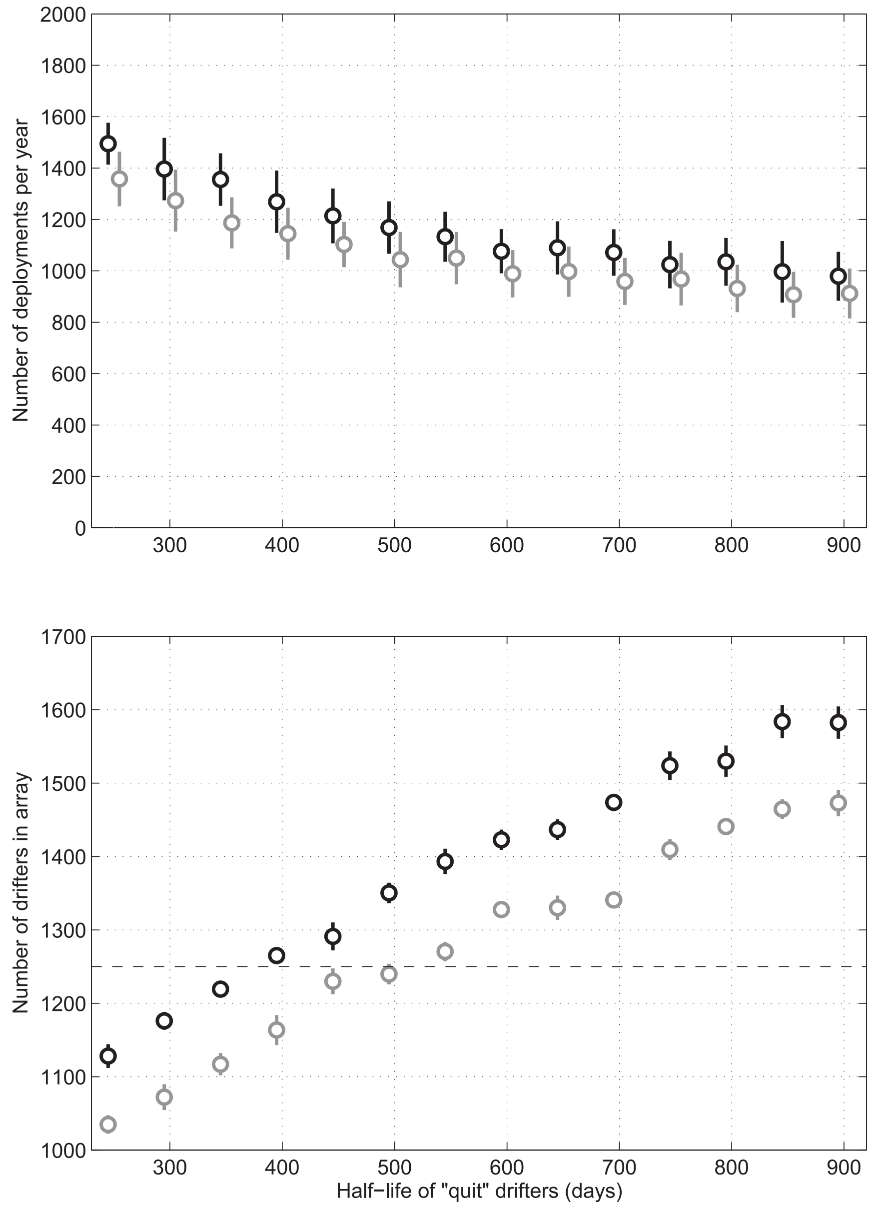

FIG. 5. (top) Number of deployments needed per year and (bottom) number of drifters in the array, in the final 2 years of the simulations as a function of "quit" half-life T_{hl}. Black dots indicate the "no tropical moorings" simulations, while gray bullets indicate the "with tropical moorings" simulations. Error bars indicate the standard deviation in the final 2 years of the simulations. A dashed line in the bottom plot indicates the goal of 1250 drifters set in GCOS-81 (UNESCO 2002).

represent an additional constraint on more spatially homogeneous deployment. Elsewhere, positive values show the need to increase deployments beyond current efforts. These positive values are found in the following regions:

- Western and northwestern Indian Ocean: It has been difficult to obtain deployment opportunities here, due to the recent threat of piracy. Hopefully, more opportunities will arise as the threat abates.
- Across the Southern Ocean sectors of the Indian and eastern Pacific Oceans: These regions are difficult to access due to the lack of shipping lines and the sporadic nature of research cruises in these regions. Additional drifters are not needed in the southern Atlantic and southwestern Pacific due to ongoing Southern Ocean deployments southeast of New Zealand and in the Drake Passage.
- East of the shipping line between Cape Town and North America, highlighting the need to enlist GDP

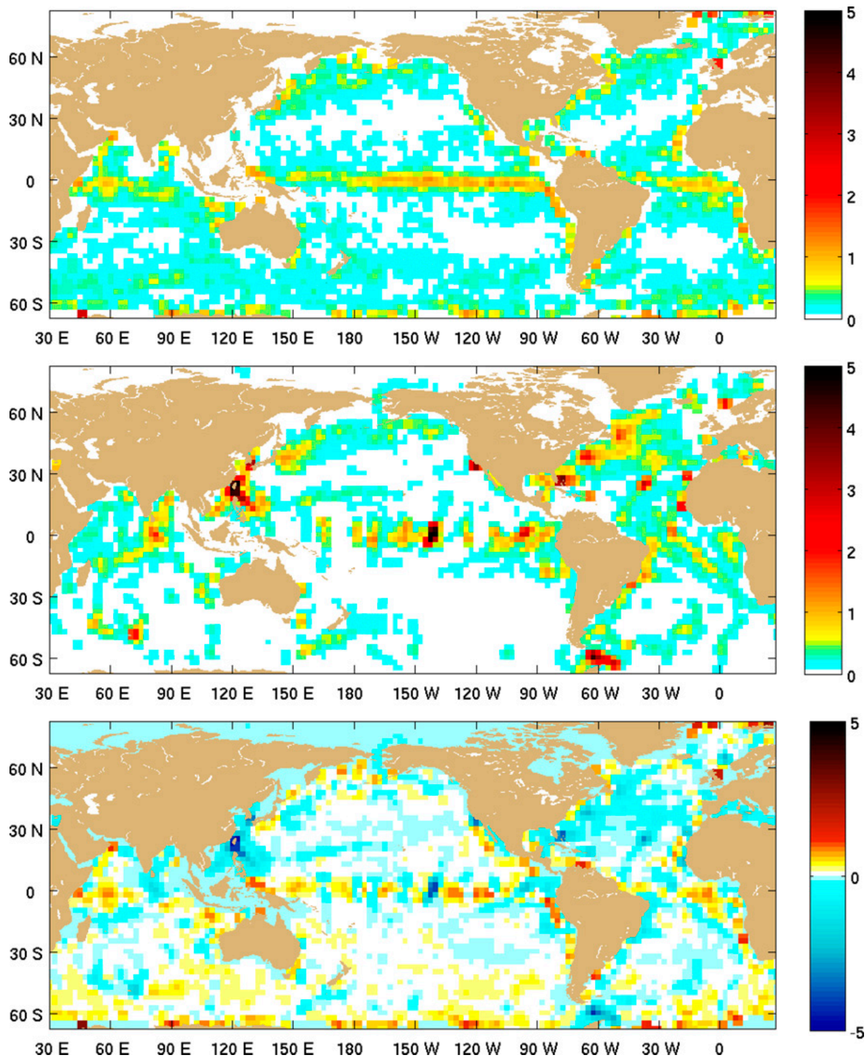

FIG. 6. (top) Drifter deployments per year needed to satisfy 5° × 5° sampling in the no-tropical-moorings simulation with T_{hl} = 450 days. (middle) Actual deployments per year averaged over the period 2006–14. (bottom) Simulated deployment needs (top) minus actual deployments (middle).

partners bordering the Gulf of Guinea and Angola basin.

- West of Mexico, Central America, and Peru, indicating the need for enhanced deployment efforts with existing GDP partners (Mexico, Peru) and the need to enlist partners in Central American countries such as Costa Rica.

4. Conclusions

A somewhat larger number of drifter deployments per year are needed for simulations that neglect the existence of a perfect tropical moored buoy array of 120 moorings between 5°S and 5°N. For example, in the no-tropical-moorings simulation with T_{hl} = 450 days, ~200 additional deployments per year are needed between 5°S and 5°N. In contrast, ~100 fewer deployments are needed between 7° and 10°N/S in the no-tropical-moorings simulation, as near-equatorial drifters move poleward to prevent gaps from developing at these latitude bands. Overall, the differences in deployment needs between the no tropical moorings and with tropical moorings are not significant compared to the variability in the simulations. This difference would be even smaller if the existing present Global Tropical Moored Buoy Array (GTMBA), rather than a perfect array of 120 5° × 5° moorings covering the near-equatorial band 5°S–5°N, was evaluated: in the period 2010–15, there were only 70 near-equatorial GTMBA sites measuring SST. Only a subset of these—28 moored buoys—measured

SSV. Thus, we conclude that there is no significant advantage to deploying drifters only outside the near-equatorial band covered (in principle) by the GTMBA. Indeed, there is value in redundancy when a mooring unexpectedly goes offline, and deployments in the near-equatorial band will quickly disperse away from the equator regardless. In addition, the drifters provide unique Lagrangian information about currents in the equatorial regions that are not measured from moorings. For example, drifters were used by Schott et al. (2004) and Perez et al. (2014) to infer the shallow near-equatorial meridional overturning cells, and by Hormann et al. (2013) to infer circulation features near the equatorial Atlantic northern cold tongue front. Consistent with these studies, Maximenko et al. (2014) derived surface circulation streamline patterns immediately north and south of the equator that were not exactly zonal (their Fig. 12.2a). One recommendation of this study is that *drifter deployments continue within the near-equatorial band also covered by the GTMBA*.

It may seem at first consideration that extending the drifter design lifetime will have unambiguously positive impacts on program costs and coverage. However, this is not true, as a more robustly engineered drifter may cost more and longer-lived drifters will tend to accumulate in the centers of the subtropical gyres, not assisting in the goal of 5° × 5° sampling. This sampling goal is not significantly aided for a design half-life exceeding ~500 days (Fig. 5). Thus, a second conclusion of this study is that *a design lifetime of ~450 days is optimal*. It is fascinating to note that the GDP arrived at this value organically over the years since 1988 (when a design lifetime of ~900 days was proposed; WMO 1988) without the benefit of simulations such as these, guided by year-to-year cost–benefit analyses. It is important to note the distinction between increased design lifetime and increased power reserve, as the latter allows new observations such as salinity, waves, current profiles, pH, etc. to be added without negatively impacting lifetimes.

For the optimal design half-life T_{hl} = 450 days, the simulations indicate that 1214 ± 107 drifters need to be deployed each year in order to maintain 5° × 5° sampling. The overall half-life of drifters in the array, including those running aground and being picked up (Fig. 4), is 246–297 days. At a cost of ~$1800 per drifter, this requires ~$2.2 million per year for instrument acquisition without considering barometer upgrades for sea level atmospheric pressure observations (Centurioni et al. 2015, manuscript submitted to *Bull. Amer. Meteor. Soc.*) or the cost of other additional sensors. Differences between simulated and actual deployment locations reflect the need to enhance deployments in the western and northwestern Indian Ocean, in the eastern subtropical to tropical Pacific Ocean, in the Gulf of Guinea and the Angola basin of the Atlantic Ocean, and across much of the Southern Ocean in the Indian and eastern Pacific basins. With perfect deployments to fill gaps in the open-ocean 5° × 5° array outside of "death zones," the array will have a steady-state size of 1291 ± 19 drifters, slightly larger than the current goal of 1250 drifters set by GCOS-81 (UNESCO 2002).

This study did not address drogue lifetimes, which—if shorter than data transmission lifetimes—would require more deployments to satisfy the OceanObs'99 conference (Needler et al. 1999) and GCOS requirements for in situ SSV. At present, drogue half-lives are 200–300 days; the GDP is expending considerable effort to increase this. Ideally, most drifters will retain their drogues for their entire data transmission lifetimes, such that the results of this study apply for both SST and SSV GCOS requirements. Without further study, it remains unclear how well the GCOS requirements for SSV translate into a maximum error in satellite-derived ocean currents, how well they allow us to resolve seasonal and lower-frequency circulation, and how these requirements translate into error estimates on climate-critical processes such as eddy fluxes of heat, salt, and momentum across time-mean ocean fronts.

A target array size somewhat larger than 1250 is consistent with the findings of Zhang et al. (2009), who assessed the maximum potential bias in uncorrected infrared-based satellite SST measurements. The WMO GCOS goal for this metric is that the bias not exceed 0.5°C (Needler et al. 1999). Zhang et al. (2009) calculated how the time-varying historical configuration of drifters, moored buoys, and ships would correct a bias of 2°C associated with a major volcanic eruption, and found that the corrected bias was a very strong function of the number of drifters in the global drifter array. The WMO GCOS goal was generally met or was slightly exceeded when the array consisted of ~1250 drifters (Fig. 6 of Zhang et al. 2009), suggesting that an array of ~1300 drifters would consistently meet this goal (assuming an historical spatial distribution at this overall size).

The third and final recommendation of this study is that *the global drifter array should be evaluated based on how well open-ocean 5° × 5° sampling is achieved* and on related metrics such as maximum potential satellite SST bias and positive impact on numerical weather prediction (Zhang et al. 2009; Centurioni et al. 2015, manuscript submitted to *Bull. Amer. Meteor. Soc.*) rather than on the array size achieving an arbitrary goal size such as 1250 drifters. The 5° × 5° bins should include the

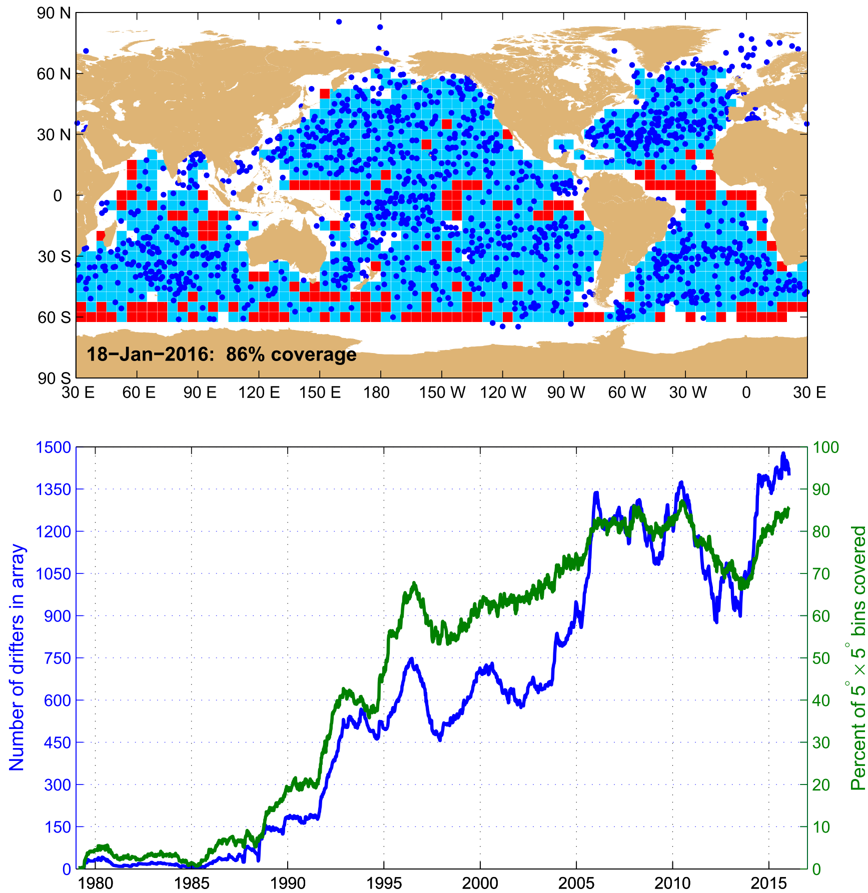

FIG. 7. (top) Global drifter array on 18 Jan 2016 (blue dots). Background shading indicates 5° × 5° open-ocean boxes excluding death zones between 60°S and 60°N, which are sampled by a drifter within 5° of their center (blue) and unsampled (red); 86% of the boxes are sampled on this date. (bottom) Time series of the number of drifters in the global array (blue) and the percent of 5° × 5° open-ocean boxes sampled by at least one drifter (green). During January 2006–December 2015, this fraction varied between 66% and 87%, with an average of 79%.

near-equatorial band also covered by the GTMBA, but it should exclude death zones, where drifter lifetimes are significantly abbreviated (Figs. 1 and 2). An example of such an evaluation is shown in Fig. 7. Such metrics are more difficult to achieve with real-life constraints on logistics but would more accurately reflect the health of the ocean observing system.

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