Removing Spurious Low-Frequency Variability in Drifter Velocities

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(Manuscript received 6 July 2012, in final form 7 September 2012)

ABSTRACT

Satellite-tracked drifting buoys of the Global Drifter Program have drogues, centered at 15-m depth, to minimize direct wind forcing and Stokes drift. Drogue presence has historically been determined from submergence or tether strain records. However, recent studies have revealed that a significant fraction of drifters believed to be drogued have actually lost their drogues, a problem that peaked in the mid-2000s before the majority of drifters in the global array switched from submergence to tether strain sensors. In this study, a methodology is applied to the data to automatically reanalyze drogue presence based on anomalous downwind ageostrophic motion. Results indicate that the downwind slip of undrogued drifters is approximately 50% higher than previously believed. The reanalyzed results no longer exhibit the dramatic and spurious interannual variations seen in the original data. These results, along with information from submergence/tether strain and transmission frequency variations, are now being used to conduct a systematic manual reevaluation of drogue presence for each drifter in the post-1992 dataset.

1. Introduction

Satellite-tracked drifting buoys (hereafter "drifters") of the Global Drifter Program (GDP) have been collecting near-surface ocean current observations in the tropical Pacific since 1979, with observations in the other basins also now spanning more than 15 years. The GDP is a branch of the National Oceanic and Atmospheric Administration's (NOAA) Global Ocean Observing System and a scientific project of the Data Buoy Cooperation Panel, and is funded by NOAA's Climate Program Office. Its objectives are to maintain a global array of ~1250 drifters and to provide a data processing system for scientific use of the resulting observations, which support short-term (seasonal to interannual) climate predictions, climate research, and climate monitoring. A subset of the drifters also includes barometers for improved numerical weather forecasting efforts. The GDP works with a large number of national and international partners in order to fulfill these goals (for more information, see http://www.aoml.noaa.gov/phod/dac/gdp_objectives.php).

Drifter data allow investigators to explore short-term climate variability of the ocean circulation and understand how it responds to changing surface forcing. However, recent studies have reported evidence of spurious variations in drifter-derived surface currents in the mid-2000s (Grodsky et al. 2011, hereafter GLC11; Rio et al. 2011; Piecuch and Rynearson 2012). These spurious variations became detectable in 2003, reached peak severity in 2006–07, and subsequently diminished (Fig. 1). GLC11 have shown that these variations have a pattern similar to mean surface winds, and that they may be explained by the presence of undiagnosed drogue loss whose occurrence changes in time.

GDP drifters have a drogue (sea anchor) centered at 15-m depth so that their trajectories reflect near-surface ocean currents (Niiler 2001; Lumpkin and Pazos 2007). When the drogue is attached, the downwind "slip" (drifter motion with respect to water motion at 15 m) is ~0.1% of the wind speed for winds up to 10 m s^{-1} (Niiler et al. 1995); when it is lost, slip increases to ~1% of the wind speed (Pazan and Niiler 2001; Poulain et al. 2009). This

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DOI: 10.1175/JTECH-D-12-00139.1

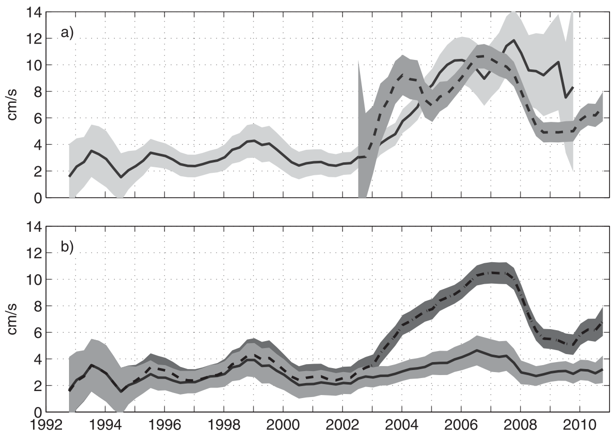

FIG. 1. (a) Annually low-passed time series of the geostrophic-removed zonal component of drifter velocity in the circumpolar latitude band 40°–60°S for the original-design drifters (solid, with light error bar) and for the redesigned minidrifters (dashed) (Lumpkin and Pazos 2007), both before the automatic drogue reanalysis. (b) Annually low-passed time series of the geostrophic-removed zonal component of drifter velocity in the circumpolar latitude band 40°–60°S before the automatic drogue reanalysis (dashed, dark standard error bars) and after (solid, medium error bars), using all (original and mini-) drifters.

increase is due to a combination of wind drag on the surface float, the vertical shear of wind-driven currents, and wave-induced Stokes drift within the upper 15 m.

Drogue presence is determined by submergence from a pair of sensors near the top of the drifter's surface float, or by a tether strain sensor at the base of the float. The more recent and accurate tether strain was developed in the early 2000s, and phased in for the entire drifter array in the period 2008–10. Current statistics from drogue-off drifters indicate that ~30% of drifters lose their drogues in the first 3 months of deployment, while nearly 90% lose their drogues in the first 1.5 years. To minimize the effect of undiagnosed drogue loss, GLC11 recommended using velocities from only the first 3 months of data currently identified as drogue on for the period January 2004–December 2008, until a full reanalysis of drogue presence could be performed. However, this interim solution eliminates ~75% of the velocity data currently identified as drogue on during this period.

The main motivation of this study is to provide the oceanographic community with a high-quality dataset of ocean currents at 15-m depth. Velocity data from drifters are often used, for example, to validate surface currents in global and regional ocean circulation models, and it is therefore crucial to remove biases from the historical archive. In this study we adapt a methodology developed by Rio (2012) to automatically reassess drogue presence for each drifter in the historical dataset since the start of continuous satellite altimetry on 14 October 1992. We demonstrate the effects of this reanalysis on time-mean and low-frequency variations in drifter velocities, and demonstrate that it significantly reduces the spurious low-frequency variations. We also demonstrate that drogue presence from submergence can be reevaluated when examined concurrently with the results of the new methodology, and that another signal—transmission frequency variations—can serve as a third drogue presence indicator. We conclude by describing how these indicators are currently being implemented by the GDP to improve the quality of the drifter data.

2. Data and methods

Surface velocities are calculated from the quality-controlled, 6-h interpolated drifter positions (Hansen and Poulain 1996) via 12-h centered differencing. The dataset in the time period 14 October 1992–11 November 2010 consists of 13 593 unique drifters.

Sea height anomalies are derived from the ⅓° gridded Segment Sol Multimissions d'Altimétrie, d'Orbitographie et de Localisation Précise/Multimission Altimeter Data Processing System (SSALTO/DUACS) delayed-time updated (up to four satellites) altimeter product of Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) (Le Traon et al. 1998). The start date of this dataset sets the date for the earliest drifters considered here, and considerably predates the onset of drogue detection problems (Fig. 3 of GLC11). Time-mean sea height is obtained from the Centre National d'Etudes Spatiales–Collecte Localisation Satellites 09 (CLS09) mean dynamic topography (MDT) product (Rio et al. 2011). Surface winds at 6 h, 0.25° resolution are obtained from the cross-calibrated multiplatform (CCMP) product (Atlas et al. 2011), derived through cross calibration and merging of ocean surface wind observations using a variational analysis method. Wind stress was calculated from CCMP wind speeds using version 3 of the Coupled Ocean–Atmosphere Response Experiment (COARE3.0) algorithm (Fairall et al. 2003). Geostrophic currents are calculated from total sea height (AVISO plus MDT) using the methodology of Lagerloef et al. (1999).

a. Automatic drogue detection reanalysis

The methodology used here to automatically detect drogue loss is based closely on Rio (2012). First, a model of the wind-driven motion of a drogued drifter is calculated as follows, using only drifters that are currently flagged as drogued and, for those after the year 2000, are less than 90 days old (this is more strict than the criterion recommended by GLC11, to be conservative). Geostrophic velocities are interpolated to drifter locations

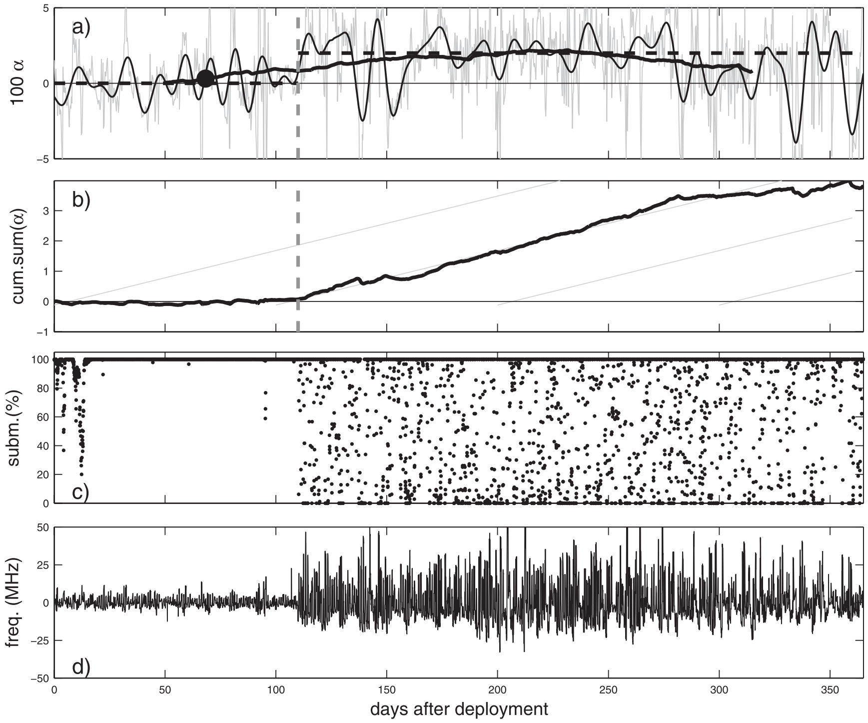

FIG. 2. (a) Time series of α (residual downwind component of drifter velocity divided by wind speed) for drifter 45975, unfiltered (gray) and low passed with a 100-day running mean (heavy black line) and low passed with a period cutoff of 10 days (thin black line). Vertical dashed line indicates a drogue-off date determined by a least squares fit of a step function (horizontal dashed lines). Black dot indicates the first date that the 100-day low pass exceeds 0.3%, the criterion used by Rio (2012). (b) Cumulative sum of α used for manual evaluation of results. Vertical dashed line repeated from (a). Sloping gray lines indicate $\alpha = 0.018$, a typical value after drogue loss, for visual reference. (c) Submergence record from drifter. (d) Transmission frequency anomalies (high passed at 2 days).

and subtracted from the in situ velocities; the resulting residual velocity components u', v', and wind stress τ, also interpolated to the drifter locations, are low passed with a period cutoff of 5 days to eliminate inertial, diurnal, and tidal motions. These residual velocities are then grouped in 2° (zonal) × 5° (meridional) × 1 climatological month bins. In each bin, a least squares best fit for the downwind velocity component u' is found of the form $u' = a\sqrt{\tau}$ and left-of-wind velocity component $v' = b\sqrt{\tau}$. In general, this statistical fitting of the ageostrophic drifter currents follows the Ralph and Niiler (1999) and Centurioni et al. (2009) approach of the form $u' \sim \sqrt{\tau/|f|}$. The latitudinal variations of the fitting coefficients a, b account for the Coriolis effect (while remaining finite on the equator), while the spatial and monthly variations allow for changes in the wind-driven response related to stratification changes (Ralph and Niiler 1999; Rio et al. 2011). If a bin has a month with fewer than 10 drifter observations, then the coefficients are not calculated but instead are filled via linear interpolation with neighboring bins for that month.

Next, having calculated a model for the wind-driven component of drogued drifters, we calculate the difference between the downwind ageostrophic, low-passed velocity of each drifter and $a\sqrt{\tau}$ interpolated to that drifter. By writing this difference as αW (Rio 2012), where W is the wind speed, we expect that $\alpha \sim 0$ for drogued drifters and $\alpha \sim 0.01$ for undrogued drifters (Pazan and Niiler 2001; Poulain et al. 2009).

In practice, we found that α tended to be larger; an examination of a subset of the data, 3160 tether strain drifters with known drogue loss, revealed that α = 0.015–0.020 after drogue loss. Drogue loss for the entire dataset was determined automatically as follows: for each drifter with more than 10 days of data, the time series of α for $W > 1.5$ m s^{-1} was fit with a step function of the form $H = 0, t < T_o; H = 0.015, t \geq T_o$, with time T_o ranging from deployment to the final data point. The value of T_o that yielded the minimum value of $(\alpha - H)^2$ is the automatically determined drogue loss time (Fig. 2a). The choice $\alpha = 0.015$ after drogue loss lies near the lower range of observed values for the 3160 tether strain drifters; larger values after drogue loss do not affect the drogue-off date determined by this approach.

The least squares fit of a step function is our largest departure from Rio (2012), who chose the first time $\langle\alpha\rangle$ exceeded 0.003 as the drogue-off date, where $\langle\cdot\rangle$ is a running 100-day average. This change was motivated by Rio's methodology tending to estimate drogue loss too early, due to cases in which $\langle\alpha\rangle$ temporarily exceeded 0.003 while the drogue was still attached. This approach also allows us to automatically detect drogue presence for time series less than 200 days long, which cannot be done with the Rio (2012) methodology; there are 5416 drifters in the study period that collected observations for less than 200 days, contributing a potential additional 1326 drifter years of velocity observations. Other changes were less significant: Rio (2012) chose a model of the form $u' \sim \tau$ and used the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA) rather than CCMP winds. The procedure described here was developed to closely reproduce the drogue-off dates of the 3160 tether strain drifters with known drogue loss.

Figure 2 shows an example of a drifter currently identified as drogue on for its lifetime in the GDP metadata. The automatic reanalysis methodology (Fig. 2a) identifies drogue loss 110 days after deployment. The time integral $\int \alpha\, dt$ (Fig. 2b) remains close to zero until drogue loss, then it increases quasi linearly with time after that. After drogue loss, the drifter's submergence (Fig. 2c) becomes noisy, but it continues to register large values that—at the recommendation of the manufacturer—were interpreted as indicating that the drogue was still present and frequently submerging the surface float.

b. Manual drogue detection reanalysis

In retrospect, and combined with information from $\int \alpha\, dt$ (Fig. 2b), the submergence record can be reevaluated to provide a more accurate drogue-off date. Additional information can be derived from the radio frequency of drifter–satellite communications, which averages 401.65 MHz and in many cases displays a regular decrease of a few megahertz during daylight due to solar heating of the surface float and related thermal expansion of the crystal resonator, which defines the frequency (G. Williams 2012, personal communication). When the drogue is lost, the magnitude of this diurnal variation often increases (Fig. 2d) due to less insulation from submergences.

A second example of drogue loss is shown in Fig. 3. As with the first example, the GDP metadata states that the drogue was attached for the entire lifetime of this drifter. In this case, the automatic detection algorithm indicates drogue loss 94 days after deployment. However, the increase in α was more gradual than in the first example, making the determination of the exact drogue loss date difficult using the automatic methodology. Changes in the behavior of submergence (Fig. 3c) and frequency (Fig. 3d) allow a more precise determination of drogue loss, which occurred 39 days after deployment.

The GDP is now engaged in a manual reevaluation of drogue presence using all three of these time series ($\int \alpha$, submergence or tether strain, and frequency), rather than solely using submergence or tether strain as in the past, for all drifters in the altimeter time period. These results are being included in periodic updates of the GDP metadata. The manual reevaluation is being conducted in order of decreasing $T_b - T_a$, where T_b is the drogue-off date according the GDP metadata and T_a is the drogue-off date given by the automatic reevaluation. As of 31 August 2012, a total of 10 112 drifters (74%) have been manually reevaluated.

3. Results and discussion

According to GDP metadata prior to the automatic reanalysis conducted here (*before*), for the period 14 October 1992–30 November 2010, 62% of the velocity measurements were collected by drogued drifters. After applying the automatic reanalysis methodology (*after*), this fraction drops to 48%. Consistent with the time series of velocity anomalies (Fig. 1) and with GLC11 (their Fig. 3), this error reached its peak in mid-2006 (Fig. 4) when the fraction of drogued drifters must be reduced from 65% (*before*) to 29% (*after*). This discrepancy diminishes to 37% (*before*) versus 23% (*after*) by the end of the study period (Fig. 4) as tether strain drifters were phased in and most of the older submergence drifters had died. During this period, the number of drifters deployed per year increased approximately linearly from ~500 in 1993–94 to ~1000 in 2008–10, with the phase in of the minidesign starting in 2003.

The time-mean difference between the undrogued and drogued drifters' zonal component of velocity (ΔU) is generally aligned with the time-mean zonal wind W_x (Fig. 5b). Consistent with previous studies (Pazan and Niiler 2001; Poulain et al. 2009), the magnitude of ΔU (before) is about 1% of W_x. However, this result is contaminated by the presence of misdiagnosed undrogued drifters that increase the wind slip of the supposedly drogued drifters, thus decreasing $\Delta U/W_x$. This effect is most prominent in the region of strong winds south of 40°S (Fig. 5c). The automatic drogue reanalysis increases the globally averaged wind slip $\Delta U/W_x$ (*after*) to 1.5%. The increase over previous estimates of $\Delta U/W_x = 1\%$ is due to the removal of a portion of the remaining undrogued drifters and to the larger relative

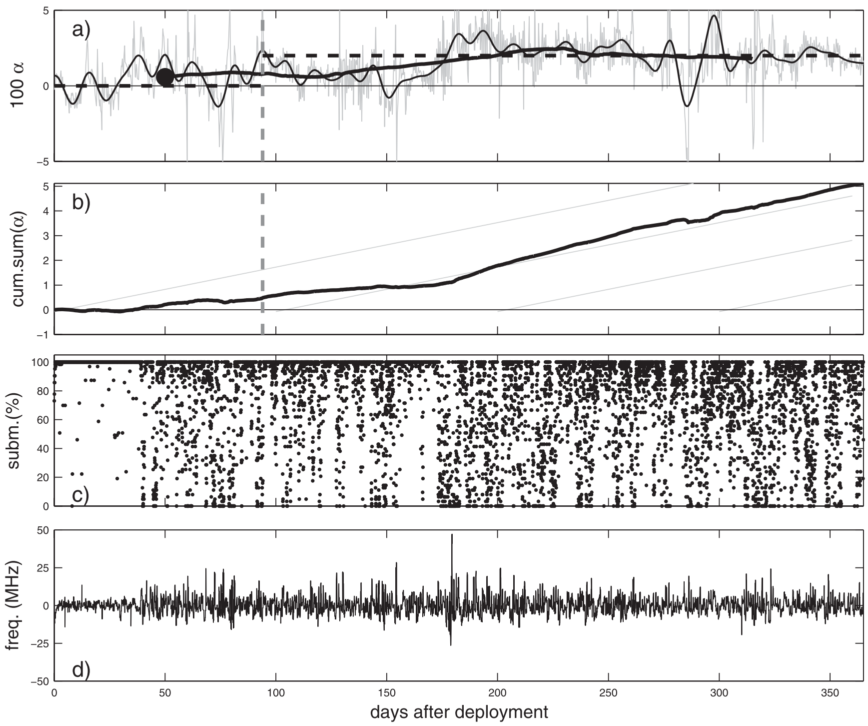

FIG. 3. (a) Time series of α (residual downwind component of drifter velocity divided by wind speed) for drifter 62587, unfiltered (gray) and low passed with a 100-day running mean (heavy black line) and low passed with a period cutoff of 10 days (thin black line). Vertical dashed line indicates a drogue-off date determined by a least squares fit of a step function (horizontal dashed lines). Black dot indicates the first date that the 100-day low pass exceeds 0.3%, the criterion used by Rio (2012). (b) Cumulative sum of α used for a manual evaluation of results. Vertical dashed line repeated from (a). Sloping gray lines indicate $\alpha = 0.018$, a typical value after drogue loss, for visual reference. (c) Submergence record from drifter. (d) Transmission frequency anomalies (high passed at 2 days).

fraction of Southern Ocean data collected since the early 2000s. This result suggests that the wind slip of undrogued drifters is approximately 50% higher than was thought before. The discrepancy with Pazan and Niiler (2001) may also be due to a larger wind slip for undrogued minidrifters, as the minidesign was phased in after that study; the global average slip of the older drifters after drogue loss is 1.4%, while the average slip of the minidrifters after drogue loss is 1.7%. By design, the two drifters move similarly while the drogue is attached.

The difference between time-mean zonal currents from the ‘‘drogue on’’ drifter *before* and *after* is spatially linked to regions of strong winds (Fig. 5a), where the wind slip correction is stronger. In particular, the westward velocity component on the equatorward flanks of the subtropical gyres (North and South Equatorial Currents) is a few centimeters per second weaker *after* than *before*. Our new estimate of the eastward flow in the Antarctic Circumpolar Current (ACC) region 40°–60°S is 4 cm s^{-1} weaker for the zonal mean (Fig. 5a), but the correction exceeds 10 cm s^{-1} at some locations, a result consistent with Rio (2012). The time variations in before currents in the ACC region (Fig. 1) contain significant spurious acceleration in the early 2000s (GLC11). This acceleration was concurrent with the phase in of the lighter and smaller minidrifter design

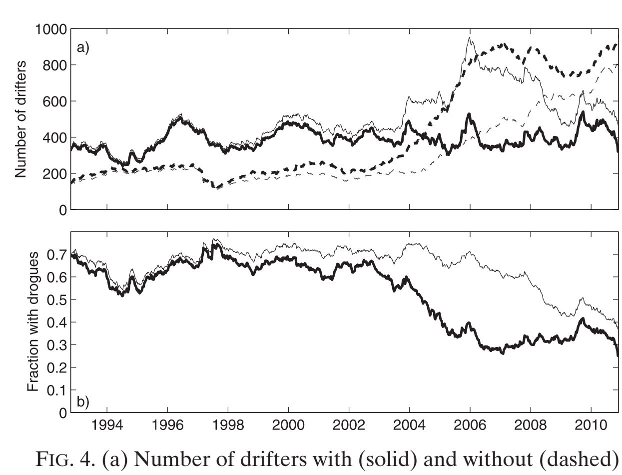

FIG. 4. (a) Number of drifters with (solid) and without (dashed) drogues, *before* (thin) and *after* (thick) automatic drogue reanalysis. (b) Fraction of drifters with drogues *before* (thin) and *after* (thick) reanalysis.

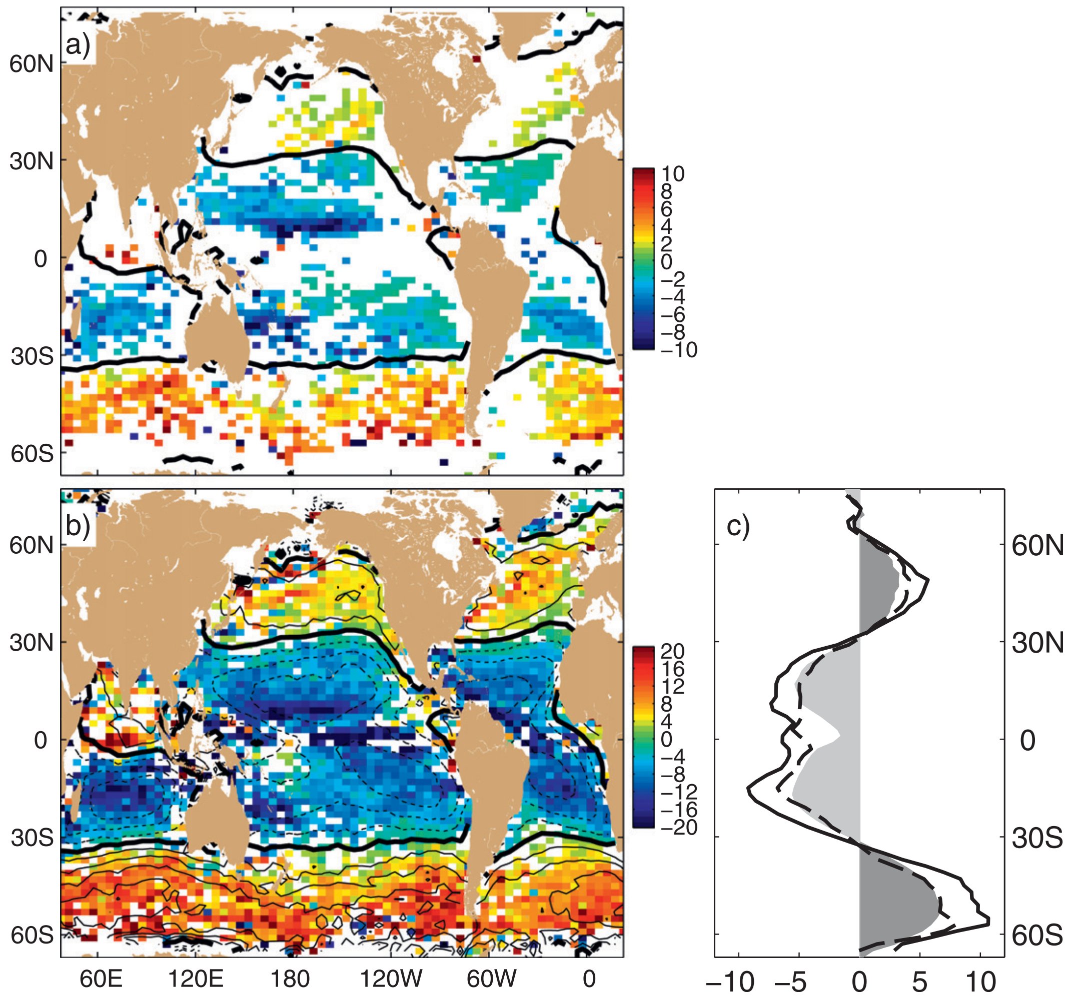

FIG. 5. (a) Difference between the mean zonal component of velocity (positive eastward) of drifters thought to have drogues *before* the automatic reanalysis and mean zonal currents *after* (cm s^{-1}), 14 Oct 1992–30 Nov 2010, with zero contour of time-mean zonal wind superimposed. (b) Drogue-off minus drogue-on (*after*) zonal component of drifter velocity (shading, cm s^{-1}). Time-mean zonal wind superimposed (2 m s^{-1} contours), westerly (easterly) wind is solid (dashed), and zero contour bold. Values not significantly different from zero are blanked in (a) and (b). (c) Time–longitude average, weighted by observation density, of mean zonal wind interpolated to the drifters (shading, m s^{-1}) and drogue-off minus drogue-on zonal component of drifter velocity (cm s^{-1}) *before* (dashed) and *after* (solid) automatic drogue reanalysis.

(GLC11) that replaced the original, larger, and more expensive design (Lumpkin and Pazos 2007). However, the acceleration is also present in the ACC speed evaluated separately from the larger original-design drifters and the newer minidrifters (Fig. 1a), indicating that the switch in design was not the cause of these low-frequency variations. By using the results of the automatic reanalysis to remove previously unidentified drogue loss, much of the low-frequency ACC variations disappear (Fig. 1b).

Although the exact cause of the drogue detection problem in the early 2000s is not clear, it was likely associated with undocumented manufacturing changes that negatively affected the performance of the submergence sensor. The detection problem was greatly alleviated by the phase in of tether strain in the late 2000s, but it was not completely eradicated because of long-lived drifters with faulty submergence (and, much more rarely, the failure of a tether strain sensor).

The lifetime of the drogues can be quantified by their half-life, that is, the number of days after which half the drifters have lost their drogues. Because a drifter can die with the drogue attached, providing a minimum estimate of the drogue lifetime, we calculate the half-life iteratively: we first use the age at death for drifters that died with the drogue still attached and the lifetimes of

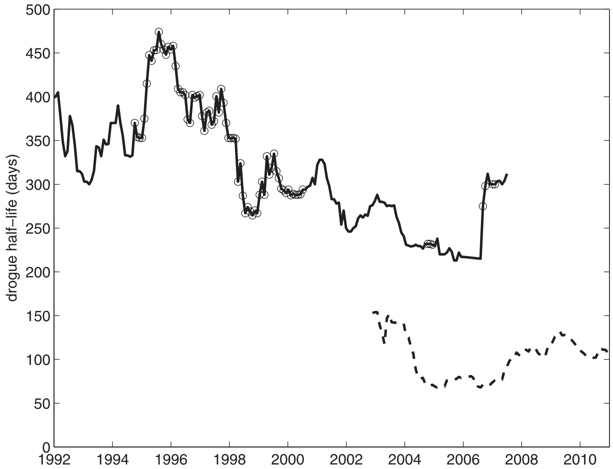

FIG. 6. Drogue half-life as a function of deployment date, calculated in a 1-yr sliding window for the original-design drifters (solid) and for the redesigned minidrifters (dashed); values are not shown if there were fewer than 50 drifters of that type deployed in the 1-yr window. Open circles indicate values for which more than half the drifters died with the drogues still attached.

the drogues for drifters that lost them. We then discard age at death values that are less than the half-life and recalculate the half-life. While there was a tendency for the resulting drogue half-life to decrease over the entire period of the study, a sharp decrease was clearly associated with the switch from the older, more robust, and more expensive drifter design to the less expensive minidrifter design (Fig. 6). The older design had an overall mean drogue half-life of 325 days, while the minidrifters have a mean drogue half-life of 104 days. The GDP is currently evaluating new tether materials and tether/drogue attachment methods with the goal of increasing drogue lifetime without significantly increasing cost. It should be emphasized that the drogue retention problem is separate from the drogue detection problem: the original-design drifters also suffered faulty or noisy submergence sensors that degraded the quality of drogue detection (Fig. 1a).

For the 10 112 drifters manually reevaluated so far, 7 have been declared ''drogue status uncertain from beginning'' due to a combination of failed or ambiguous submergence/strain, and ambiguous results from α and frequency. For the rest, drogue-loss dates from the automatic method T_a and the manual reevaluation T_m compare favorably, with a median $T_a - T_m$ of 1.25 days, mean of 32.5 days, and standard deviation of 112.7 days. The mean and standard deviation are dominated by positive outliers; and 637 drifters (6%) have $T_a - T_m > 90$, that is, manual drogue-loss date 90 days or earlier than given by the automatic reanalysis. There are various reasons why the automatic routine was not accurate for these drifters. In some cases α increased gradually (as in Fig. 3). In other cases α increased in two clearly defined steps, suggesting an initial partial drogue loss (chosen in the manual reevaluation) followed later by a complete drogue loss at the date determined by the automatic methodology. Finally, many drifters with large $T_a - T_m$ were located near the centers of the subtropical gyres, where locally weak wind may result in insignificant slip, while submergence and/or frequency variations indicate drogue loss.

The results of the manual reevaluation are being included in updates of the GDP metadata. Drogue-off dates from this study's automatic drogue reanalysis, and ongoing results from the manual reevaluation, are available online (at ftp://ftp.aoml.noaa.gov/phod/pub/lumpkin/droguedetect/). Drifter-derived monthly climatological currents (available at http://www.aoml.noaa.gov/phod/dac/dac_meanvel.php) are updated to reflect this drogue reanalysis.

Acknowledgments. The authors thank three anonymous reviewers for their valuable input. This research was supported by the NOAA Climate Program Office's Climate Change Data and Detection Program. RL was additionally supported by NOAA's Atlantic Oceanographic and Meteorological Laboratory.

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