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Spurious trends in global surface drifter currents

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[1] The Global Drifter Program (GDP) has been measuring near-surface ocean currents with surface drifters since 1979. At least half of the World Ocean now has drifter velocity time series longer than 15 years. The availability of this data opens new opportunities to explore observationally how ocean circulation responds to changing surface forcing. In this paper we report evidence of an apparently spurious acceleration of global surface drifter currents. This rapid acceleration occurs in a pattern reflecting the geographic distribution of mean surface winds. For example, in the westerly wind region of the Southern Ocean this strengthening is at least 0.5 cm/s per year eastward, while in the easterly trade wind region of the tropics this strengthening is on average 0.25 cm/s per year westward. One possible explanation we explore is that the bias is due to the presence of some undrogued drifters whose frequency of occurrence changes in time and whose windage is significantly greater than that of the drogued drifters. This paper is dedicated to the memory of Professor Peter Niiler, who first suggested this explanation. **Citation:** Grodsky, S. A., R. Lumpkin, and J. A. Carton (2011), Spurious trends in global surface drifter currents, *Geophys. Res. Lett.*, *38*, L10606, doi:10.1029/2011GL047393.

1. Introduction

[2] Horizontal transports in the oceanic mixed layer play a key role in a wide variety of physical, chemical, and biological processes [e.g., *Johnson*, 2001; *Grodsky and Carton*, 2002; *Lumpkin and Garzoli*, 2005]. The global drifter data set, collected mainly as an outcome of the Surface Velocity Program (SVP, now GDP), has been developed since 1979 in order to monitor the spatial and temporal changes of these currents throughout the world ocean at a nominal depth of 15 m, [*Niiler et al.*, 1995; *Reverdin et al.*, 2003; *Lumpkin and Pazos*, 2007]. Thus for parts of the ocean where the instruments were first deployed, such as the tropical Pacific, the records of surface velocity now span three decades. However, their usefulness for interannual to decadal climate studies depends on identification and correction of systematic errors. In the tropical Pacific, for example, we expect changes in zonal surface currents to reflect changes in the strength of zonal wind stress and any difference in the trends of these variables suggests bias in one or the other data set [*Clarke and Lebedev*, 1997]. In this study we examine the global surface drifter data set for the presence and possible causes of spurious long-term trends in near-surface currents whose presence would compromise the usefulness of the data set for climate studies.

[3] The SVP drifters consist of a spherical surface buoy connected to a submerged nylon 'holey sock' drogue which allows the drifter to track the horizontal motion of water parcels at a nominal depth of 15 m. Most of these devices have been manufactured by four companies, Technocean, Metocean, Pacific Gyre, and Clearwater. In 2002, in order to reduce manufacturing costs, a new, more compact design was presented in the Data Buoy Cooperation Panel Specification revision 1.2. In this mini-drifter redesign, the nondimensional ratio of the drag exerted by the drogue to the drag exerted by all other components was maintained at a constant value of 40:1 in order to try to constrain wind-forced downwind slip relative to the 15 m current to be less than 0.1% of wind speed [*Niiler et al.*, 1987, 1995].

[4] One well-known source of systematic error in drifter currents results from a mechanical failure of the buoy-drogue connection which is vulnerable to breakage because of constant flexing. When the drogue is lost, wind slippage increases from O(0.1%) to about 1% of the wind speed [*Niiler and Paduan*, 1995; *Poulain et al.*, 2009] through a combination of wind drag on the exposed portions of the buoy, and the impact of vertical shears of wind-driven current and wave-induced Stokes drift in the upper 15 m. Studies of this problem at NOAA's Surface Drifter Data Assembly Center (SD-DAC) indicate that approximately 30% of drifters lose their drogues in the first three months after deployment and nearly 90% in the first 1.5 years.

[5] The original method for detecting whether a drogue is attached ("drogue-on") was indirect and used submergence data from a pair of sensors in the surface float. A sudden decrease in the time spent submerged was used to infer drogue loss. In the early 2000s Clearwater, which has manufactured 1/3 of the drifters in the global array, began replacing the submergence detectors with a tether strain gauge which monitors the tension in the buoy-drogue connection. But the switch of all drifters from the four major manufacturers (representing 99% of the global array) to the use of tether stain gauges has only occurred in the last half of 2010, and older drifters with submergence sensors are still present in the array. Experience at the SD-DAC suggests that use of the tether strain gauge has significantly improved detection of drogue loss. But difficulties in drogue presence detection raise the possibility that the current archive of "drogue-on" data may in fact contain a non-negligible number of mislabeled undrogued drifters. Their presence in the archive could provide an explanation of the presence of an apparent downwind acceleration of surface currents in analyses based on supposedly "drogue-on" surface drifter data.

2. Data

[6] This study uses pseudo-Eulerian currents obtained from Lagrangian trajectories of the 14,840 SVP drifter

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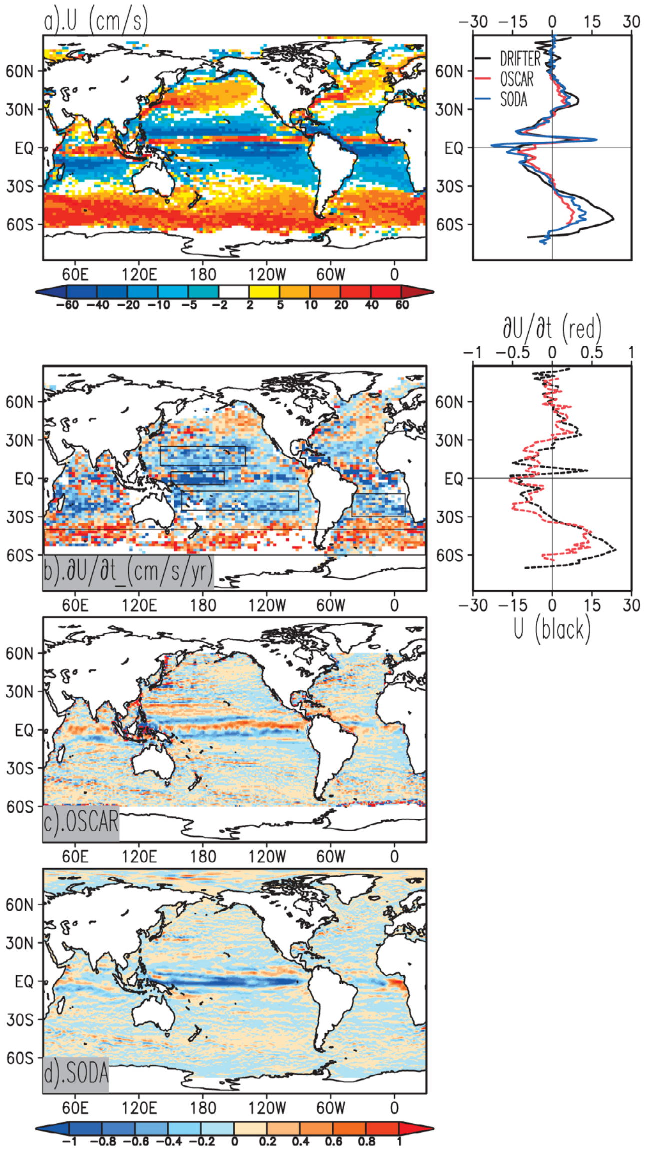

Figure 1. (a) Time mean zonal current (U) from "drogue-on" drifters; time mean zonal acceleration ($\partial U/\partial t$) from: (b) "drogue-on" drifters, (c) OSCAR, (d) SODA. Figure 1a (right) shows zonal mean U from various datasets. Figure 1b (right) shows zonal mean U and $\partial U/\partial t$ from "drogue-on" drifters.

currents available as of September, 2010, interpolated to regular 6 hr time intervals (12 hr centered difference of 6 hr interpolated positions [*Hansen and Poulain*, 1996]). Note that binning may also introduce bias in estimates of mean flow [see, e.g., *Lumpkin*, 2003]. When binned into 3° longitude by 2° latitude by one month bins the drifter data in each bin has an average time series length of 13.6 years. The longest records of up to 32 years are available in the tropical Pacific while the record length decreases to just a few years at polar latitudes. We explore the possible presence of bias in the surface drifter currents by analyzing the following three subsets of the data. These subsets are based on the existing (currently operational) method of drifter drogue presence detection: Drogue-off drifters identified as undrogued; "Drogue-on" drifters identified as drogued (quotes emphasize that a fraction of the "drogue-on" drifters may be undrogued); and truly drogue-on drifters which are "drogue-on" drifters during their first 3 months since deployment. The latter dataset is a useful proxy for a set of drifters genuinely containing drogues since drogue loss has an approximately uniform probability distribution in time (~70% of the drifters deployed within 3 months or younger retain their drogues according to the SD-DAC census of drogue lifetimes).

[7] An alternative assessment of drogue presence is done based on the ratio of ageostrophic drifter current (difference between observed drifter current and geostrophic surface current) to local wind. Winds are provided by the cross-calibrated, multi-platform (CCMP), multi-instrument ocean surface wind velocity of *Atlas et al.* [2011] for the period 1987–2009 (podaac.jpl.nasa.gov/DATA_CATALOG/ccmpinfo.html). The geostrophic component (u_g) of drifter currents are calculated by applying the geostrophic approximation to altimetry-based AVISO sea level anomalies (www.aviso.oceanobs.com) combined with the time mean dynamic topography of *Rio et al.* [2011]. Close to the equator a second order geostrophic approximation is used [e.g., *Lagerloef et al.*, 1999]. To calculate the residual ageostrophic drifter velocity, the geostrophic velocity and winds are interpolated onto the drifter trajectories in space and time and low-pass filtered with a 5-day running mean. These data are available only since October 1992 through November 2009 due to the availability of altimetry and scatterometer winds.

[8] We also explore the possible presence of bias in the surface currents by comparison of the drifter currents to two independent analyses of surface current. The first is the Ocean Surface Current Analysis – realtime (OSCAR) of *Bonjean and Lagerloef* [2002]. This analysis is based on combining geostrophic currents computed from satellite altimetry with ageostrophic currents computed from the surface wind stress. The second is the Simple Ocean Data Assimilation (SODA) 2.2.4 reanalysis of *Carton and Giese* [2008] which uses data assimilation to ingest historical hydrographic information, and SST into a meteorologically forced ocean general circulation model.

3. Results

3.1. Time Mean Currents

[9] One way to evaluate the drifter currents for the presence of bias is to examine the global data for consistency with our expectations and with independent data including models. Time-mean drifter zonal currents agree with previous assessments and capture the main features of the global circulation including the eastward component in the western boundary currents, the North Equatorial Counter Currents in the North Pacific and Atlantic Oceans, the westward trade wind currents, and the eastward Antarctic Circumpolar Current (ACC) in the South Ocean (Figure 1a).

[10] Noticeable difference between drifter currents and the two other data sets is observed in the ACC where the time mean zonal drifter current is about 10 cm/s faster than either OSCAR or SODA. Time mean zonal winds in this region are 10 m/s which *Niiler and Paduan* [1995] suggest will lead to an O(10 cm/s) additional slippage due to drogue loss. This suggests at least a part of the difference can be attrib-

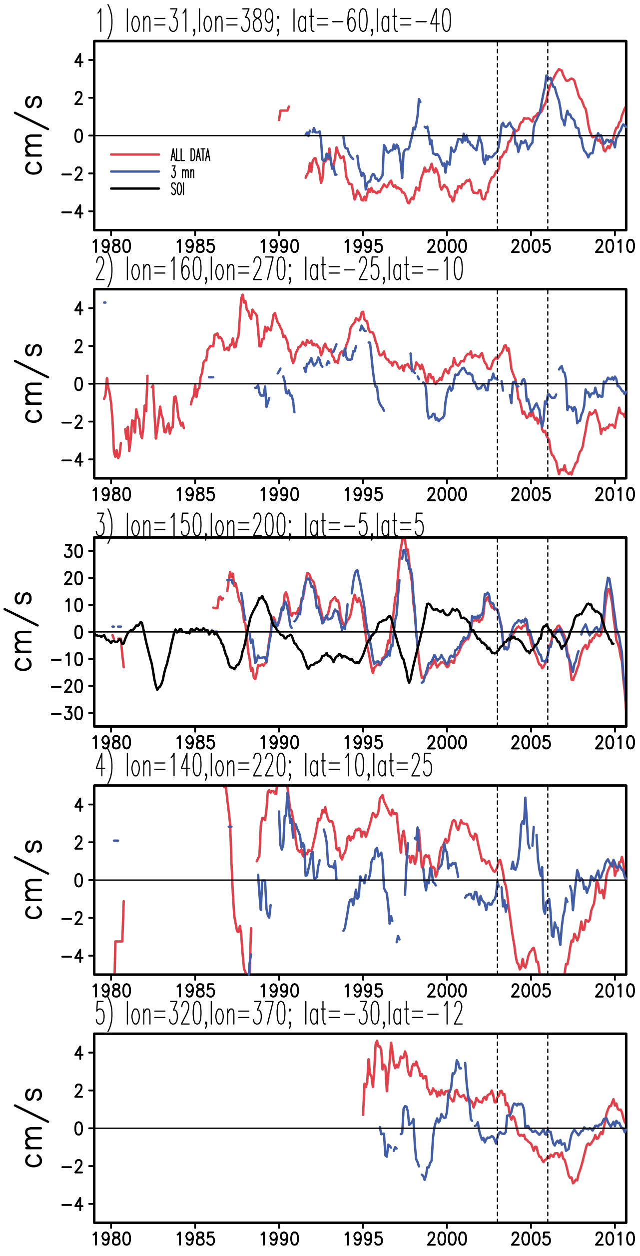

Figure 2. Boxed averaged anomalous zonal velocity (see Figure 1b for box locations) for (red) all "drogue-on" drifters and (blue) "drogue-on" drifters younger than 3 months. All data are yearly low-pass filtered. The Southern Oscillation Index (SOI, black) is also shown in the third panel. The interval 2003–2006 is marked with dashed lines. Note an apparent reduction in the long-term changes of currents for 3-month young drifters, although some aspects of interannual variability may be not well sampled by 3-month young drifters.

uted to problems with drogue presence detection and unaccounted wind slippage.

3.2. Temporal Trend in Drifter Currents

[11] We next consider the slope of linear trend in time (time mean acceleration, u_t) of anomalous zonal currents referenced to the monthly climatological currents at each grid point (Figure 1b). The zonal acceleration u_t shows unexpected pronounced large scale patterns suggesting that zonal velocity accelerates in the direction of the time-mean zonal currents (Figure 1b, right). In the Southern Ocean u_t is at least 0.5 cm/s per year eastward, while in the trade wind regions u_t is around 0.25 cm/s per year westward. Arguably the ACC may have truly been accelerating due to an observed strengthening of the local westerly winds, in turn reflecting a strengthening (since the late 1970s) of the Southern Annular Mode [*Visbeck*, 2009]. But this trend vastly exceeds what we would expect from climate models that show only a moderate (less than 10%) strengthening and a poleward shift of the ACC [*Fyfe and Saenko*, 2006]. Elsewhere we think a physical explanation of the observed trend is also questionable. For example the trade winds do not seem to be accelerating in the same way the trade wind currents observed by drifters do. In contrast to climate model simulations that predict deceleration of the northern flank and acceleration of the southern flank of the ACC, the observed zonal velocity acceleration suggests a strengthening of the entire current (Figure 1b).

[12] In order to find some confirmation for the observed trend in near-surface currents we have compared the observed trend to that computed over similar time interval using fields from SODA and OSCAR. Those comparisons indicate that westward acceleration in the equatorial belt has occurred in all three during recent decades although the detailed patterns differ (Figures 1b–1d). Away from the equatorial zone SODA and OSCAR show weaker accelerations than the drifter data, and similarly in the Southern Ocean SODA and OSCAR show much weaker acceleration than the drifters (Figure 1b).

[13] One possible explanation for the large magnitude of the zonal velocity trend in the drifter currents and its positive correlation with the spatial pattern of the time mean currents and winds is offered by a change in the drogue design in the early 2000s. If the redesigned mini-drifter has a different response to currents than the original SVP drifter, the change in drogue design could account for the differences in observed and expected current acceleration. Directly testing this explanation, however, requires information about the design of each individual drifter, information which is currently being compiled.

[14] An alternative explanation is that the number of unidentified undrogued drifters has changed in time (first increasing, now possibly decreasing) related to the change to mini-drifters in the early 2000s and the introduction of direct drogue detection method in the late 2000s. Temporal changes in the contamination of the "drogue-on" data by undrogued data would lead to temporal changes in wind slip in "drogue-on" data, thus explaining at least part of the spurious acceleration seen in Figure 1b. To test this explanation we next compare anomalous zonal velocity (deviation from the monthly seasonal cycle) from the existing "drogue-on" drifter data with that from a sub-sample limited to drifters deployed within 3 months or less (truly drogue-on). If changes in the drogue detection were part of the problem, we would expect to see a reduction in the zonal current acceleration in the truly drogue-on sub-sample. What we find is that in all off-equatorial regions the truly drogue-on data have weaker long term changes of currents than the "drogue-on" data (Figure 2). In the equatorial Pacific intense storms with strong vertical shear are uncommon but ENSO related interannual variability is large (Figure 2,

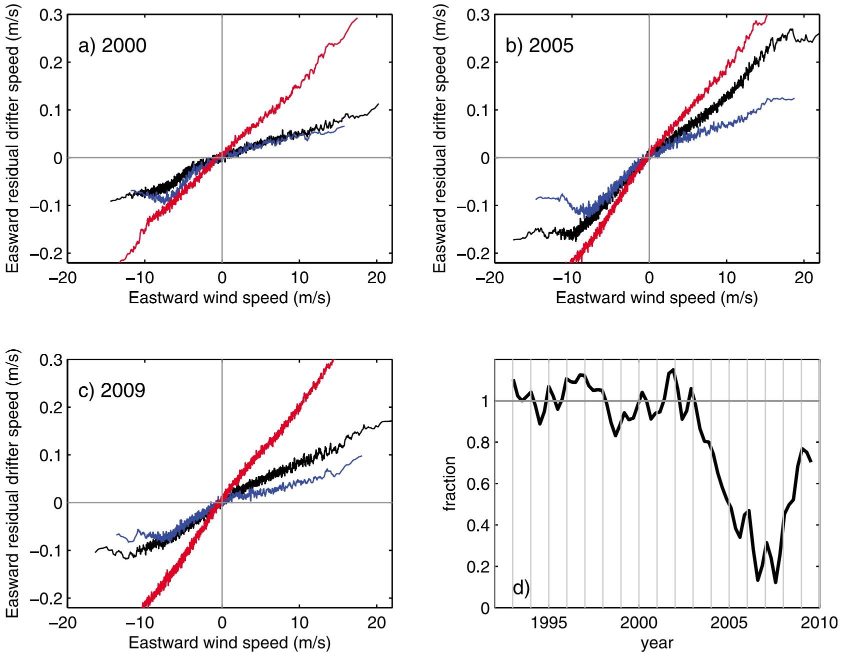

Figure 3. Eastward residual speed of drifters after removing geostrophic component, averaged as a function of eastward wind speed, in the year (a) 2000, (b) 2005, and (c) 2009. Each point in each graph is the average of 1000 measurements sorted versus zonal wind. Black: data for "drogue-on" drifters that may contain data for undrogued drifters due to problems in drogue detection method. Blue: data for "drogue-on" drifters less than 3 months old, a proxy for truly "drogue-on" drifters. Red: undrogued drifters. (d) Fraction of drogue-on drifters in dataset diagnosed as truly having drogue attached, based on relative slopes of residuals vs. wind in the wind speed range 0–10 m/s, calculated using a sliding 180 day window. Note: the fraction can exceed 1 due to uncertainties in the slope estimate.

middle, note change in the y-axis limits). Here, interestingly, drifter currents lead the Southern Oscillation Index by several months [cf. *Lumpkin et al.*, 2010]. Perhaps as a result of the lack of intense storms the difference between "drogue-on" and truly drogue-on currents is only a weak downwind drift of a few cm/s, a difference which is much smaller than the striking interannual variability.

3.3. Assessment of Drogue Detection

[15] The apparent acceleration of the "drogue-on" drifters relative to truly drogue-on drifters strongly suggests the presence of a time dependent bias in drogue detection and resulting changes in wind slippage of drifters [e.g., *Niiler and Paduan*, 1995; *Poulain et al.*, 2009]. Here we attempt to isolate wind slippage as a function of drifter age. The drifter zonal speed is decomposed into three velocity components:

$$u(z) = u_g + u_{slip} + u_w(z) \qquad (1)$$

where (u_g) is the geostrophic, (u_{slip}) the wind-induced slip, and u_w (z) the ageostrophic wind-driven components. For a drogued drifter z = 15 m, but for an undrogued drifter z = 0 m. The wind-related residual current consists of the second two terms in (1): $\Delta u = u - u_g$. For drogued drifters (marked with superscript d), $\Delta u^d = u^d_{slip} + u_w$ (z = 15), while for undrogued drifters (marked with n), $\Delta u^n = u^n_{slip} + u_w$ (z = 15), where the actual wind slip and wind-driven current shear in the upper 15 m are combined in an effective wind slip of undrogued drifters (u^n_{slip}). This effective wind slip is the ageostrophic component of drifter motion relative to the ageostrophic motion of the water at 15 m depth. It is assumed above that vertical shear of u_g is negligible in the upper 15 m layer. But, in basins with shallow mixed layers (like the Black Sea) this may be not true. In open ocean conditions *Niiler and Paduan* [1995] point to wind-driven motion as the source of most of the difference.

[16] Residual wind-related zonal drifter currents show a positive linear relationship to wind speed in the range 0–10 m/s for each of the three drifter datasets (Figure 3). The slope (α) of this relationship, of course, characterizes the drifter response to wind as well as the 15 m wind-driven current shear. Undrogued drifters feel a stronger residual wind effect (α^n = 0.018 based on drogue-off data from the 1992–2009). Truly drogue-on drifters, in contrast, have a weak relationship where α^d = 0.0047. "Drogue-on" drifters (which, as discussed above, we believe include some undrogued drifters) have an intermediate value α = 0.0090. Assuming a linear contribution to slippage by the undrogued drifters, the ratio, $f = (\alpha - \alpha^d)/(\alpha^n - \alpha^d)$ = 67%, gives the fraction of undrogued drifters in the "drogue-on" data set for the period 1993–2009. It is striking that the slopes α^d and α^n don't change much for various years, but the slope of "drogue-on" cluster does (Figure 3). This suggests that the fraction of "drogue-on" drifters truly having drogues on has varied with time. There are regional variations in the magnitude of the fraction of truly drogued drifters. The fraction is higher in the Atlantic and Pacific and lower in the Indian Ocean. This regional difference suggests that drogue life varies among manufacturers, since their deployment is not homogeneous from one basin to the next. We also note some differences in wind slip for easterly and westerly winds. These differences need further examination and may

be attributed to differences in the vertical scale of wind-driven currents in the tropics and mid-latitudes (easterly and westerly winds, respectively).

[17] Examination of α^d for different years shows that the problem of unidentified undrogued drifters in the "drogue-on" data set arose sometime around late 2003 to early 2004 and steadily become worse until 2006–2007 (Figure 3). Then, very likely due to the phase-in of tether strain gauge technology, the problem gets better by end 2009. Interestingly, the time series of anomalous currents in Figure 2 also indicates significant changes in drifter currents during that same time period. Ultimately, these drifter current changes during the 2000s are the major cause of the spurious temporal trends evaluated over longer periods. Also note that the anomalous behavior of drifter currents does not seem to depend on the particular drogue manufacturer. We suspect, although cannot yet verify, that the reduced effectiveness of the submergence drogue detection technique is in fact a result of the switch to the smaller mini-drogue design.

4. Summary

[18] The Global Drifter Program has been providing observations of global near-surface ocean currents since the late 1970s at high spatial and temporal resolution. But their usefulness as Climate Data Records requires identifying and removing subseasonal time-dependent bias. In high wind/wave regions like the ACC, the time mean zonal drifter velocity is around 10 cm/s faster than corresponding estimates from an ocean reanalysis (SODA) or an independent observation-based estimate (OSCAR). This discrepancy suggests the presence of non-negligible wind slip which can be accounted for by contamination of "drogue-on" data by undrogued drifters, which have an order of magnitude stronger wind slip.

[19] The evidence for a time dependent component to the bias comes from examination of temporal linear trends. Surface currents computed from the "drogue-on" data accelerate in the direction of the time-mean current throughout the World Ocean. In the Southern Ocean this acceleration is at least 0.5 cm/s per year eastward, while in the trade wind regions it is on average 0.25 cm/s per year westward. The most likely explanation for this apparent strengthening of current is also the erroneous inclusion in the "drogue-on" data of undrogued drifters. This hypothesis is supported by considering a sub-sample of "drogue-on" data that excludes all drifters 'older' than 3 months. SVP statistics suggest that only 30% of drifters lose their drogues during the first 3 months after deployment. In all off-equatorial regions the 3 month 'young' drifter data displays weaker acceleration of currents in comparison with the entire "drogue-on" data.

[20] Examination of the ageostrophic component of drifter velocity and its relationship with winds shows that the problem of unidentified undrogued drifters in the "drogue-on" data set arose sometime around late 2003 to early 2004 and steadily become worse until 2006–2007. Then, very likely due to the phase-in of tether strain gauge technology, the problem gets better by end 2009. This result suggests the need to improve the drogue presence detection method for drifters that didn't have the tether strain sensor. The best way to develop this technique would be to test it on newer drifters that have the sensor. In their future research the authors will focus on the reasons for the 2000s drogue detection failure and exploring ways to correct these data. Until this reassessment is complete, we recommend that users interested in exclusively drogue-on data use only the first 90 days of data for drifters in the time period January 2004 through December 2008.

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