Behavior of ALACE Floats at the Ocean Surface

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Short title: BEHAVIOR OF ALACE FLOATS AT THE OCEAN SURFACE
Abstract. Autonomous Lagrangian Circulation Explorer (ALACE) floats were designed to measure subsurface velocities throughout the global ocean. In order to transmit their data to satellite, they spend 24 hours at the ocean surface during each 10 to 25 day cycle. During this time the floats behave as undrogued drifters. In the Southern Ocean, in accordance with Ekman theory, floats tend to be advected to the left of the wind during their time at the surface. Mean displacements are likely to carry floats northward and correspondingly, with each cycle, the Southern Ocean floats will move into warmer water with higher dynamic height. Because of large variability, the northward trend may not be discernible for any single float: in two years worth of 10 day cycles, a typical float will be displaced $100 \pm 270$ km northward relative to a float that never surfaces. Float velocities and wind speed are statistically correlated at the 95% confidence level. Floats tend to move more rapidly than drogued drifters, are more sensitive to changes in wind speed, and are less subject to the Ekman effect than drogued drifters. Regression coefficients estimated from the differences between float and drogued drifter velocities suggest that floats may be used to estimate the mean upper ocean currents in regions where drogued drifter data are not available.
1. Introduction

Autonomous Lagrangian Circulation Explorer (ALACE) floats were developed in the late 1980s and have been deployed globally since the early 1990s to study mid-depth ocean circulation [Davis, 1992, 1998]. The success of the ALACE floats has led to a number of successor float designs, now being deployed through the Argo float program. The floats are equipped with an inflatable bladder and a pump so that they can adjust their buoyancy to travel between the surface and a fixed depth below the surface. ALACE floats spend most of their time at mid-depth, typically about 900 m, but are programmed to rise to the surface every 10 to 25 days in order to transmit to satellite their position, mean temperature, and in some cases vertical temperature and salinity profiles. Using current technology, floats spend about 24 hours at the surface in order to contact a System Argos satellite and relay all of their information. This study focuses on the behavior of ALACE floats at the ocean surface.

In order to ensure that their antennas are above the water so that they can reliably contact the Argos satellites, ALACEs are designed to have substantial buoyancy at the ocean surface [Davis, 1992]. Because the floats ride far above the waterline, they tend to behave like undrogued surface drifters. Thus they are expected to be accelerated by the winds and waves and therefore to deviate from the surface ocean currents [Pazan, 1996].

Since ALACE floats may be displaced substantially by the wind at the surface and by surface intensified currents, they do not necessarily rejoin the same mid-depth streamline or water mass on consecutive dives. Therefore most studies have treated successive velocity estimates from the same float as statistically independent and unrelated quantities [Davis et al., 1996; Davis, 1998; Gille, 2001]. However, the actual behavior of the floats at the surface has not been quantified, and some indications suggest that the trajectories obtained from each of the ALACE floats may resemble trajectories from nonsurfacing floats [LaCasce, 2000].

Rather than analyzing data from the entire globe, in this study we specifically concentrate on the Southern Ocean. Section 2 discusses the data used in this study. In section 3, we quantify the displacement of ALACE floats by surface currents as well as wind and wave
motions. Section 4 examines the possibility of removing the wind slip from ALACE surface velocities, in much the way that wind slip is removed from undrogued surface drifters, in order to study upper ocean circulation. Results are summarized in section 5.

2. Data

2.1. ALACE Floats

For this study, we analyzed a total of 15,027 velocity observations from 302 ALACE floats operating in the Southern Ocean between 1990 and 2000. Surface velocities inferred from these records are shown in Figure 1a. These represent mean velocities averaged over the 24-hour period that the floats spend at the surface. Davis [1998] estimated the uncertainty in surfacing and diving positions to be 1 to 3 km. Observations are densest in the South Atlantic, where substantial numbers of floats were deployed, and in the Antarctic Circumpolar Current (ACC), where strong currents advect floats rapidly to provide extensive spatial coverage. The mean surface speed of the floats was $25.9 \pm 0.8$ cm s$^{-1}$, and their mean direction at the surface was $6.7^\circ \pm 1.2^\circ$ to the north of due east. (Here, and throughout this paper, error bars assigned to means are standard errors, computed as $2\sigma/\sqrt{N}$, where $\sigma$ is the standard deviation and $N$ the number of independent samples.) We also compared each surface motion with the subsurface float velocities observed immediately before and after surfacing. We considered only the times when subsurface float velocities indicate eastward advection (with motions between $\pm 90^\circ$ of due east). In these cases, surface velocities are rotated toward the north by an average of $3^\circ \pm 1^\circ$ relative to subsurface velocities.

2.2. Mean Temperature and Dynamic Height

We compared ALACE floats with surface and subsurface temperature and dynamic height. These data were derived from the atlas compiled by Gouretski and Jancke [1998], gridded at 1° resolution, and dynamic height was computed relative to 3000 m depth.
Temperature and dynamic height contours both run predominantly from west to east. For example, at the locations where floats rise to the surface, surface temperature contours have a mean orientation of $-0.5^\circ \pm 0.3^\circ$ just barely south of due east, and surface dynamic height contours are oriented $4.3^\circ \pm 0.4^\circ$ slightly to the north of due east.

2.3. Wind Fields

In order to examine float response to wind forcing, we used 10-m wind fields derived from the National Centers for Environmental Prediction (NCEP) reanalysis [Kalnay et al., 1996]. NCEP winds are reported at 6-hour intervals, with a spatial resolution of about $1.9^\circ$. We used the following procedure to interpolate NCEP winds onto float locations: First, for each 24 hour interval that a float spent at the surface, we identified a starting point in time and space, an ending point, and 3 equally-spaced intermediate points. We then linearly interpolated the 6 hour winds onto these 5 points. For each surface displacement, mean winds were determined by averaging the five interpolated winds. Average winds are eastward, with a mean speed of $8.09 \pm 0.03$ m s$^{-1}$ and a mean orientation of $-7.8^\circ \pm 0.6^\circ$ slightly to southeast.

Since winds vary slowly in space but rapidly in time, the correlation between float and wind velocities was significantly affected by the temporal averaging technique. Float velocities are more strongly correlated with mean winds computed using interpolated 6 hour winds than they are with winds determined from 24-hour average wind fields.

In order to verify that winds and floats were well matched, we examined the correlation between wind and float velocities by projecting the float velocities into along-wind and cross-wind components. The interpolated winds are related to simultaneous along-wind and cross-wind float velocities with correlation coefficients of 0.29 and 0.11 respectively. Both correlations are statistically significant at the 99% level (meaning that in no more than 1% of randomly generated datasets, would an equivalent level of correlation be observed.) The correlation coefficient between winds and the cross-wind component of float velocity increases to 0.13 when compared with winds 18 hours earlier, as illustrated in Figure 2.
difference is statistically significant at the 74% level. This suggests that the component of the float motion in the direction of the wind responds instantly to wind fluctuations, while the component of float motion that is perpendicular to the wind responds with an 18 hour delay. This time delay is consistent with the spin up of inertial oscillations in the ocean mixed layer in response to changes in wind forcing. The implications of this lagged correlation will be explored elsewhere, and for simplicity this analysis makes use only of the zero lag wind observations.

2.4. Surface Drifters

Drogued surface drifters were used to provide a benchmark in order to evaluate float behavior at the surface. This study employed 12 years of daily drifter observations from the Southern Ocean collected between 1989 and 2000, as depicted in Figure 1b. Drifter coverage is not as extensive as ALACE coverage within the ACC, but is more extensive in the region north of the ACC. Drifter data were archived at daily intervals, 6-hour NCEP winds were interpolated onto the drifter locations, and drifter data were corrected for wind slip. Details of the drifter data are summarized by Niiler et al. [1995] and by Pazan and Niiler [2001]. The drifter velocity observations were calculated to decorrelate in 2 to 4 days and the a priori error was estimated to be 0.02 m s\(^{-1}\).

3. Float Displacement at the Surface

Some of the methodologies that have been developed to study traditional subsurface Lagrangian floats make use of the long trajectories that are obtained by tracking floats several times a day using acoustic techniques [e.g. O’Dwyer et al., 2000; LaCasce, 2000]. ALACE floats do not lend themselves to the same type of analysis, because they spend 24 hours at the ocean surface during each 10 to 25 day cycle. In this section we evaluate the distance and direction that ALACE floats travel at the ocean surface.

We analyzed surface float displacements relative to reference fields defined by geographic
coordinates, time-mean dynamic height, or time-mean temperature contours. In order to fully consider the changes in float properties as a result of surface displacements, dynamic height and temperature were examined both at the surface and at 900 m. The subsurface depth of 900 m was chosen to be representative for this study, because most of the ALACE floats were ballasted to depths between 700 and 1100 m. Surface float displacements can be represented by two-component vectors oriented relative to the reference fields. The “along-stream” component of float displacement is zonal for a reference field defined by geographic coordinates and on average nearly zonal for reference fields defined by dynamic height or temperature. Southern Ocean currents tend to be surface intensified but unidirectional throughout the water column, so mean surface streamlines do not differ substantially from mean subsurface streamlines. The “cross-stream” component of float displacement moves floats perpendicular to the reference field.

Figure 3 shows empirical probability density functions (PDFs) of the displacement velocities of ALACE floats at the ocean surface relative to geostrophic streamlines. These PDFs do not differ visibly from PDFs of the displacement velocities relative to temperature contours or geographic coordinates (not shown). Zonal and along-stream velocities (solid line) show a positive mean, indicating that the surface displacements are eastward, in the same direction as the wind and aligned roughly along contours of temperature or dynamic height. PDFs of meridional or cross-stream velocities (dashed line) are centered near zero but are on average positive, implying northward transport at the surface. This is consistent with a mean Ekman transport oriented to the left of the Southern Ocean winds. The widths of the PDFs in Figure 3 indicate that there is substantial variability about the mean. In particular, cross-stream surface motions may be difficult to distinguish from a random walk centered around the mean geostrophic streamlines.

Table 1 summarizes the statistics of the float velocities. The first part of the Table shows mean velocities at the surface relative to geographic, dynamic height, and temperature contours. The second part indicates mean velocities at 900 m depth, estimated by projecting
the float observations from depths between 700 and 1100 m depth onto the 900 m depth surface, as discussed by Gille [2001]. Along-stream surface float velocities are roughly 3 to 4 times greater than along-stream subsurface velocities. Thus in 24 hours at the surface, a float is likely to travel the same along-stream distance that it would in 3 or 4 days at 900 m depth. Cross-stream surface velocities are an order of magnitude larger than cross-stream subsurface velocities, which are barely distinguishable from zero at the 95% significance level. Thus for a float that spends 10 days at 900 m for every 1 day at the ocean surface, at least 50% of cross-stream motions will be due to surface processes.

As a result of cross-stream surface motions, on average the surface temperature and dynamic height of the water surrounding the float will increase during the time that the float spends at the surface. In addition, when the float resubmerges, it is expected to return to a water mass that is warmer and has higher dynamic height than the water from which it came. To quantify these changes, we interpolated time-averaged mean atlas data from Gouretski and Jancke [1998] onto the beginning and end points for the surface displacements.

Table 2 summarizes the average changes in dynamic height and temperature that would be expected as a result of 24-hour displacements. The first part of the table shows the expected increase in surface properties. In a typical 24 hour period at the surface, an ALACE float is expected to move into water that is $0.1 \pm 1.6$ dynamic cm higher and $0.01 \pm 0.20^\circ C$ warmer than the water where it started. (Error bars in Table 2 are errors of the mean, while results discussed here in the text are errors for single realizations. Both represent two standard deviation errors.) The second part of the table shows that as a result of this surface advection, a float ballasted to 900 m depth would typically return to water that was $0.04 \pm 0.71$ dynamic cm higher and $(3 \pm 67) \times 10^{-3}^\circ C$ warmer than the water in which it floated in the previous cycle. The final segment of Table 2 shows the expected change in subsurface properties as a result of a 1-day displacement at 900 m depth. In contrast with surface velocities, subsurface velocities are on average oriented along mean dynamic height or temperature contours. In a statistically averaged sense, subsurface motions change neither the dynamic height nor the temperature of
the water surrounding the floats.

In 2 year’s worth of 10 day cycles, a float will spend about 70 days at the surface. These results indicate that in this time, a typical float is likely to be displaced 540±380 km eastward and 100±270 km northward relative to a float that never rose to the surface. At 900 m depth, this is equivalent to an average change of 0.027±0.120 dynamic meters and 0.22±1.10°C. Thus for an individual float, the impact of spending time at the surface may not have a discernible pattern, but for the collective data set, surface processes are likely to result in a northward advection and statistically significant change in temperature and dynamic height that could not be attributed to subsurface processes. Moreover, temperature and dynamic height shifts are likely to be largest where gradients are sharp, within the Antarctic Circumpolar Current. Surface displacements should be taken into account in computations of extended time period float behavior and they are likely to be particularly important for conventional dispersion calculations that examine the statistics governing the gradual separation of two floats launched from the same location [e.g. Taylor, 1921; LaCasce and Bower, 2000].

4. Surface Circulation from Floats

Surface displacements may make longterm ALACE trajectories difficult to interpret, but they also have the potential to tell us about surface ocean circulation. Pazan and Niiler [2001] (henceforth PN01) explored the possibilities of estimating the wind slip of undrogued surface drifters by comparing the wind responses of drogued and undrogued drifters. Here we apply analogous methods to the ALACE drift velocities from the ocean surface.

Float speeds at the surface exceed mean geostrophic speeds by a factor of 10. While objectively mapped geostrophic velocities are expected to be low compared with instantaneous velocities, the order of magnitude difference in velocities suggests that the floats are accelerated by the wind, and behave like undrogued drifters. PN01 used two-dimensional complex regressions to determine the dependence of
drogued and undrogued drifter velocities on wind speed. We use the same type of regression model to determine the dependence of ALACE float and drogued drifter velocities on winds. We seek relationships of the form:

\[ U_f = A_f + B_f W_f \]  
\[ U_d = A_d + B_d W_d \]  

where \( U_f \) and \( U_d \) represent vector velocities of floats and drogued drifters respectively. \( W_f \) and \( W_d \) correspond to vector wind velocities that have been interpolated onto the float and drogued drifter positions and times. The complex coefficients \( A_f, B_f, A_d, \) and \( B_d \) were computed by linear regression.

To derive mean coefficients for this study, all data were used if they fell within 3 standard deviations of the mean velocities and came from the region south of 30°S. Drifter data represent repeated measurements from the same instruments, and are estimated to decorrelate on time scales of 2 to 4 days. Therefore we assumed that one third of drifter observations were statistically independent. In contrast, since surface float observations are separated in time by at least 8 days, all float observations were assumed to be statistically independent. Table 3 summarizes the magnitudes and angular orientations of the fitted coefficients. The angle of \( B \), \( \phi_B \), is larger for the drogued drifter data than it is for the ALACE floats, implying that drogued drifters are advected more clearly to the left of the wind than are floats. This is not surprising, since the subsurface drogues of the drifters are deeper within the Ekman layer than the surface floats are. As a result drifters are likely to be advected more to the left of the wind and less strongly downwind than surface floats.

Following the framework developed by PN01, we sorted the float and drifter data collected between 30°S and 60°S into 2° latitude by 8° longitude bins (2×8). Since Southern Ocean flow is predominantly zonal, we also considered 1° latitude by 360° longitude bins (1×360). For each bin we computed separate sets of regression coefficients. Bins were
selected for further analysis if they contained at least 25 float observations and if no more than 20\% of the drifter observations were provided by a single drifter. In addition, we required that the difference between the wind speeds for drifters and floats be 1 m s\(^{-1}\) or less and that the float and drifter mean wind directions differed by no more than 30\°. PN01 also mandated that the mean winds be between 3 and 8 m s\(^{-1}\), but this criterion proved impractical in the Southern Ocean since it would have eliminated all of the bins located in the ACC region. As with the mean coefficients derived above, float and drifter velocities were excluded from the calculation if they differed from the local mean by more than 3 standard deviations.

Like PN01, we assumed that \(W_f = W_d\) and subtracted (2) from (1) to obtain a relationship for the difference between float and drifter velocities:

\[
U_f - U_d = A_f - A_d + (B_f - B_d)W_f \\
= A_\Delta + B_\Delta W_f
\] (3)

In principle, the coefficients \(A_\Delta\) and \(B_\Delta\) can be used to simulate drogued drifter speeds from observed wind and float velocities. Figure 4 shows estimates of the magnitudes (\(|A_\Delta|\) and \(|B_\Delta|\)) and angular orientations (\(\phi_{A_\Delta}\) and \(\phi_{B_\Delta}\)) of the regression coefficients as a function of latitude for the 2×8 bins and for the 1×360 bins. For the 2×8 case, the regression model explains about 60\% of the rms float variability and 47\% of the rms drifter variability, while for the 1×360 case it captures 32\% of the rms float variability and 29\% of the rms drifter variability.

The amplitude \(|A_\Delta|\) estimates the constant difference between float and drifter speeds at the same location and experiencing the same wind conditions. In their earlier comparisons of drogued and undrogued drifters, PN01 reported that \(|A_{\Delta_{PN}}| = 0\) m s\(^{-1}\). In contrast, in these float-drifter comparisons, \(|A_\Delta|\) was statistically different from zero at the 95\% level in most bins. Figure 4a shows estimates of \(|A_\Delta|\) as a function of latitude. The 2×8 bin weighted mean of \(|A_\Delta|\) is 0.046±0.002 m s\(^{-1}\), while for the 1×360 bins it is smaller, averaging 0.021±0.001
m s$^{-1}$. This mean offset may indicate that drifters and ALACE floats respond differently to surface currents, which are not part of the regression model, or the offset may stem from deficiencies in the available wind observations. $|A_\Delta|$ shows no strong latitudinal dependence suggesting no simple geographic origin for the mean offset.

The angular orientation estimate $\phi_{A_\Delta}$ indicates the orientation difference between constant (non-wind forced) component of the float and drogued drifter velocities. In this study, for both the 2×8 case and the 1×360 case, $\phi_{A_\Delta}$ has a weighted mean value of 58°±2°. Individual angular differences, shown in Figure 4, span a broad range of angles. The fact that these differ from zero indicates that the background drifts of the floats and drifters are not necessarily oriented in the same direction, possibly because of spatial or temporal sampling differences for the two data sets.

ALACE floats are strongly influenced by winds. In Figure 4c, $|B_\Delta|$ quantifies the wind-forced separation between drifters and floats. The weighted mean of PN01’s $|B_{\Delta_{PN}}| = (8.9 \pm 0.1) \times 10^{-3}$. In our analysis, for 2×8 bins, $|B_\Delta|$ has a mean value of $(11.1 \pm 0.2) \times 10^{-3}$, and for 1×360 bins $|B_\Delta|$ averages $(9.4 \pm 0.1) \times 10^{-3}$. Both estimates slightly exceed the mean obtained from PN01’s analysis, which may suggest that ALACE floats are more responsive to wind than undrogued drifters because of their high buoyancy at the surface. The 2×8 results are broadly scattered and show no clear trend, but the 1×360 results increase towards the equator.

For both 2×8 and 1×360 bins, the angle $\phi_{B_\Delta}$ (Figure 4d) are near zero, with weighted means of $-1.5 \pm 1.0$ and $2.5 \pm 1.0$ respectively. These estimates agree with the weighted mean of PN01’s angles, $-1.4 \pm 0.5$ and show no strong latitudinal trend. This suggests that wind-forced undrogued motion is aligned in the direction of the wind.

What accounts for the latitudinal trend in $|B_\Delta|$ in the 1×360 bins? Figure 5a shows the magnitudes of the coefficients $|B_f|$, $|B_d|$ and $|B_\Delta|$ for this case. The magnitudes of $|B_f|$ and $|B_d|$ are nearly constant at all latitudes and cannot explain any significant latitudinal change in $|B_\Delta|$. Instead the difference is due to the angular orientation of the coefficient $B$. Figure 5b
shows the angular orientations $\phi_{B_d}$ and $\phi_{B_f}$. Drifters are strongly deflected to the left of the wind, with a mean angle $\phi_{B_d} = 134 \pm 4^\circ - (1.82 \pm 0.01)\theta$. The direction of drifter motion relative to the wind is expected to depend on the depth of the 15 m drogue relative to the depth of the Ekman layer, which is generally thought to be deeper at higher latitudes than at mid-latitudes [Ralph and Niiler, 1999]. In contrast, floats are located at the top of the Ekman layer and show no strong latitudinal dependence. Figure 5b indicates that they are deflected slightly to the left of the wind, with an average angle $\phi_{B_f} = 34 \pm 3^\circ - (0.29 \pm 0.06)\theta$, where $\theta$ is latitude. The angular difference between $\phi_{B_f}$ and $\phi_{B_d}$ is the major factor explaining the latitudinal dependence of $|B_\Delta|$. This latitudinal trend did not appear in the 2×8 bin analysis, because comparatively few bins were available for the latitude ranges between 50° and 60°S and between 30° and 40°S.

Since the spatial variation in $B_\Delta$ is a real effect, it should be taken into account. Our analysis shows that $A_\Delta$ and $\phi_{A_\Delta}$ do not depend on latitude. The term $\phi_{B_\Delta}$ shows a slight latitudinal dependence, but this effect is not clearly a significant. On the basis of this analysis, in the Southern Hemisphere the best fit coefficients for $A_\Delta$ and $B_\Delta$ in (3) are:

\[
\begin{align*}
|A_\Delta| &= 0.021 \pm 0.001 \text{ m s}^{-1}, \\
|B_\Delta| &= (1.78 \pm 0.07) \times 10^{-2} - (1.8 \pm 0.1) \times 10^{-4}\theta, \\
\phi_{A_\Delta} &= 58^\circ \pm 2^\circ, \\
\phi_{B_\Delta} &= 2.6^\circ \pm 1.0^\circ
\end{align*}
\]

Estimates of drogued drifter behavior made from undrogued ALACE floats are likely to be noisy because of uncertainties in wind fields and background flow, but may give realistic large-scale flow patterns in regions of the world that are otherwise difficult to sample.
5. Summary

This study has analyzed the behavior of ALACE floats at the surface of the Southern Ocean. All of the floats deployed during the 1990s as part of the World Ocean Circulation Experiment relied on System Argos satellites to transmit their data to land. Transmission required that the floats spend 24 hours at the surface during each float cycle of 10 to 25 days. Because of windage and the Ekman effect, during their time at the surface Southern Ocean floats tended to move northward relative to temperature isolines, dynamic height contours, and lines of latitude. Nonetheless, even in the high wind region of the Southern Ocean, floats tend to travel further along streamlines than across them. This analysis indicates that in the course of 70 days at the surface, representing two year’s worth of 10 day cycles, a typical float would move $540\pm380$ km eastward and $100\pm270$ km northward relative to a float that never surfaced. As a result of this northward displacement, the mean temperature of a 900 m deep float would be expected to increase by $0.22\pm1.10^\circ$C and the mean dynamic height to rise by $0.027\pm0.120$ dynamic meters.

Surface float motions are statistically correlated with NCEP winds at the 95% level. In least-squares fits to wind velocity data, undrogued floats have larger regression coefficients than drogued drifters, indicating that the undrogued floats respond more strongly to wind than drifters do. Differences between float and drifter regression coefficients vary as a function of latitude, primarily because drifters rotate further to the left of the wind at mid-latitudes than they do at high latitudes. The latitudinal dependence is linear in the geographic region studied here. Using derived coefficients, the upper ocean currents seen by drogued drifters can be reconstructed from undrogued floats in combination with wind fields.

The successors to ALACE, dubbed Argo floats, will be deployed extensively over the next decade to monitor global climate variability. Argo planners hope to take advantage of new global telecommunications satellites in order to shorten the time period that the floats need to spend at the ocean surface which would make long-term dispersion analysis possible using float data. Logistical and financial difficulties faced by the global satellite programs may
delay the implementation of high-speed telecommunications systems and yield an extended data set of day long surface displacements. Results of this study suggest that these surface velocity records can be used as a complement to surface drifter data sets. Ultimately, if global satellite coverage is available, Argo floats are likely to spend an hour or less at the surface during each cycle. With sufficient averaging, even these short duration surface displacements could be used to detect surface currents, although the inferred velocities will be sensitive to small positioning errors and are therefore likely to be noisy.

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References


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Figure Captions

**Figure 1.** Geographical distribution of float and drifter data in the Southern Ocean: (a) ALACE floats surface velocities between 1990 and 2000. (b) Drogued surface drifter velocities between 1989 and 2000.

**Figure 2.** (a) Correlation coefficient of wind speed and along-wind component of float velocity as a function of the time separation between wind and float observations. (b) Same thing for wind speed versus the cross-wind component of float velocity.

**Figure 3.** Probability density functions of ALACE float velocities at the ocean surface: (dashed line) along-stream velocity component and (solid line) cross-stream velocity component. Surface displacements are calculated relative to dynamic topography at 900 m depth (referenced to 3000 m depth) from the *Gouretski and Jancke* [1998] atlas.

**Figure 4.** Magnitude and angle of the difference between regression coefficients computed for ALACE float and drogued drifter velocities as functions of wind speed. Regression coefficients were computed in bins with dimensions 2° latitude by 8° longitude (open circle) and 1° latitude by 360° longitude (solid line). Their magnitudes and phases are shown as functions of latitude. Error bars indicate 95% confidence intervals. (a) Magnitude of the constant offset, $|A_\Delta|$. (b) Orientation angle of the constant offset, $\phi_{A_\Delta}$. (c) Amplitude of the wind coefficient, $|B_\Delta|$. (d) Angular orientation of the wind coefficient, $\phi_{B_\Delta}$.

**Figure 5.** Magnitude and angular orientation of regression coefficients between ALACE float (dashed line) and drogued drifter velocities (solid line) as functions of wind speed, plotted at different latitudes, as discussed in the text. (a) Magnitude of $B_f$, $B_d$ and $B_\Delta$. The weighted mean values of $|B_f|$ and $|B_d|$ are $(13.6 \pm 0.1) \times 10^{-3}$ and $(5.74 \pm 0.01) \times 10^{-3}$ respectively. $B_\Delta$ is related to the latitude: $|B_\Delta|= 1.78 \pm 0.07 \times 10^{-2} - 1.8 \pm 0.1 \times 10^{-4} |\theta|$. (b) Phase of wind response, $\phi_{B_f}$ and $\phi_{B_d}$. 
Tables
Table 1. Typical velocity displacements of ALACE floats at the surface and at 900 meters depth, relative to lines of latitude, temperature contours, and dynamic height relative to 3000 m. As discussed in the text, temperature and dynamic height at the surface and at 900 meters depth are derived from hydrographic atlas data mapped by Gouretski and Jancke [1998].

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<td>1.9 ± 0.4</td>
<td>1.4 ± 0.4</td>
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velocity at 900 m depth (cm s\(^{-1}\))

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<td>−0.11 ± 0.14</td>
<td>−0.17 ± 0.12</td>
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Reported errors of the mean are 2 times the standard deviation divided by \(\sqrt{N}\).
Table 2. Typical changes in properties of ALACE floats in 24 hrs relative to temperature contours, and geostrophic streams at the surface and 900 m in depth relative to 3000 m. As discussed in the text, temperature and dynamic height at the surface and at 900 meters depth are derived from hydrographic atlas data objectively mapped by Gouretski and Jancke [1998].

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<th>Dynamic Height</th>
<th>Temperature</th>
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<td>(1.1 ± 0.3) × 10^{-2} ° C</td>
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<td>N (# obs.)</td>
<td>12176</td>
<td>14694</td>
</tr>
<tr>
<td><strong>change in properties at 900 m resulting from 1 day at the surface</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>(3.9 ± 1.3) × 10^{-2} cm</td>
<td>(3.1 ± 1.1) × 10^{-3} ° C</td>
</tr>
<tr>
<td>N</td>
<td>12176</td>
<td>14355</td>
</tr>
<tr>
<td><strong>change in properties at 900 m during 1 day at 900 m</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>(2.6 ± 4.8) × 10^{-3} cm</td>
<td>(2.5 ± 3.6) × 10^{-4} ° C</td>
</tr>
<tr>
<td>N</td>
<td>9256</td>
<td>11753</td>
</tr>
</tbody>
</table>

Reported errors of the mean are 2 times the standard deviation divided by √N.
Table 3. Magnitude and angle of regression coefficients from equations (1) and (2).
Observations used in this analysis are drawn from the latitude range between 30° and 60°S.

<table>
<thead>
<tr>
<th></th>
<th>ALACE floats</th>
<th>Drogued Drifters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>A</td>
<td>$</td>
</tr>
<tr>
<td>$\phi_A$</td>
<td>$15.8^\circ \pm 0.5^\circ$</td>
<td>$1.4^\circ \pm 0.1^\circ$</td>
</tr>
<tr>
<td>$</td>
<td>B</td>
<td>$</td>
</tr>
<tr>
<td>$\phi_B$</td>
<td>$19.7^\circ \pm 0.2^\circ$</td>
<td>$52.2^\circ \pm 0.1^\circ$</td>
</tr>
<tr>
<td>$N$ (# obs.)</td>
<td>14346</td>
<td>290527</td>
</tr>
</tbody>
</table>
Figure 1. Geographical distribution of float and drifter data in the Southern Ocean: (a) ALACE floats surface velocities between 1990 and 2000. (b) Drogued surface drifter velocities between 1989 and 2000.
Figure 2. (a) Correlation coefficient of wind speed and along-wind component of float velocity as a function of the time separation between wind and float observations. (b) Same thing for wind speed versus the cross-wind component of float velocity.
Figure 3. Probability density functions of ALACE float velocities at the ocean surface: (dashed line) along-stream velocity component and (solid line) cross-stream velocity component. Surface displacements are calculated relative to dynamic topography at 900 m depth (referenced to 3000 m depth) from the Gouretski and Jancke [1998] atlas.
Figure 4. Magnitude and angle of the difference between regression coefficients computed for ALACE float and drogued drifter velocities as functions of wind speed. Regression coefficients were computed in bins with dimensions 2° latitude by 8° longitude (open circle) and 1° latitude by 360° longitude (solid line). Their magnitudes and phases are shown as functions of latitude. Error bars indicate 95% confidence intervals. (a) Magnitude of the constant offset, $A_j$. (b) Orientation angle of the constant offset, $\Phi_A$. (c) Amplitude of the wind coefficient, $B_j$. (d) Angular orientation of the wind coefficient, $\Phi_B$. 
Figure 5. Magnitude and angular orientation of regression coefficients between ALACE float (dashed line) and drogued drifter velocities (solid line) as functions of wind speed, plotted at different latitudes, as discussed in the text. (a) Magnitude of $B_f$, $B_d$ and $B_\Delta$. The weighted mean values of $|B_f|$ and $|B_d|$ are $(13.6 \pm 0.1) \times 10^{-3}$ and $(5.74 \pm 0.01) \times 10^{-3}$ respectively. $B_\Delta$ is related to the latitude: $|B_\Delta| = 1.78 \pm 0.07 \times 10^{-2} - 1.8 \pm 0.1 \times 10^{-4} |\theta|$. (b) Phase of wind response, $\phi_{B_f}$ and $\phi_{B_d}$. 