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Key Points:
- Targeting deployments according to a jet reference frame is useful for understanding Agulhas Leakage
- Inconsistent bias exists between satellite-derived geostrophic velocities and drifter velocities
- Further drifter deployments will aid in disentangling to sources of uncertainty

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The Use of a Jet Reference Frame to Analyze Drifter Trajectories in the Agulhas Current

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Abstract Studies based on drifters that are deployed using fixed geographical locations can alias the variability in the Agulhas Current. Numerical model simulations have shown that tracking particles using jet coordinate systems will improve our understanding of the variability in western boundary currents. In this study we use in situ observations to show the potential of quasi-Lagrangian measurements with an investigation into the relationship of the upstream surface velocity configuration and the trajectories surface drifters follow. Additionally, we use these drifters, along with ship-based measurements, to expose biases in satellite-derived geostrophic velocities in the Agulhas Current. Between September 1992 and October 2017, 49 surface drifters crossed the altimeter track #096 in a nonmeandering state. Of the 49 surface drifters, 16 crossed inshore of the surface velocity maxima, 3 of which leaked into the South Atlantic Ocean. Biases between altimetry-derived geostrophic velocities and absolute velocities from ship acoustic Doppler current profiler and drifters measurements have pointed toward surface drifters leaking from inshore of the Agulhas Current core in a region of high shear. However, the bias between these velocities is inconsistent, with the highest range in bias found inshore of the Agulhas Current core. Due to the lack of data in the Agulhas Current and various sources of error, much work remains to be done and results presented here may provide motivation for further targeted drifter deployments in the future.

Plain Language Summary In this study we use a combination of surface drifters and satellite-derived surface velocities over the Agulhas Current to investigate the relationship between the structure of the surface velocities and the path the surface drifters follow. Between September 1992 and October 2017, 49 surface drifters crossed the altimeter track #096 in a nonmeandering state of the Agulhas Current. Of the 49 surface drifters, 16 crossed inshore of the surface velocity maxima, 3 of which leaked into the South Atlantic Ocean. In doing this investigation we also found inconsistencies between the surface speeds derived from the satellite and that of the surface drifters and ship-based measurements. These inconsistencies are likely due to processes such as wind or small-scale features, which satellites are unable to measure; other factors may be the unknown shape of the geoid and thus mean state of the ocean in these regions. The Agulhas Current is an under sampled region; thus, this study could be used for motivation to deploy more surface drifters in the region. Studies like this will improve our understanding of how water from the Agulhas Current enters the South Atlantic Ocean.

1. Introduction

The Agulhas Current is the western boundary current of the South Indian Ocean. It flows along the east coast of southern Africa and is distinguished by two regimes. In the northern Agulhas Current, the flow is stable due to the very narrow, steep shelf slope (Paldor & Lutjeharms, 2009). This contrasts with the southern reaches, where the shelf slope begins to relax as the bathymetry widens into the large, triangular area of the shelf known as the Agulhas Bank (Lutjeharms, 2006).

The interaction of the Agulhas Current with this dynamic shelf relief has been the subject of several theoretical and modeling studies. These studies have shown that the widening of the shelf onto the Agulhas Bank has a strong influence on the amount of Agulhas Current water leaked into the Atlantic Ocean (Speich et al., 2006), upwelling and the configuration of the inshore front (Gill & Schumann, 1979; Lutjeharms et al., 2000), and the generation of cyclonic eddies (Lutjeharms et al., 2003; Penven et al., 2001). However, our understanding of the dynamics of this interaction remains limited. This is especially true at scales approaching the submesoscale, where observations have become available only recently and are very limited in time and space (Krug et al., 2017).

Agulhas Leakage is the leaking of warm saline water from the Indian Ocean into the South Atlantic Ocean. This leakage changes the thermohaline properties in the Atlantic and thus plays a significant role in the long-term stability of the Atlantic Meridional Overturning Circulation (Beal et al., 2011; Holton et al., 2016). Several studies have shown that Agulhas Leakage is dominated by mesoscale eddies (or Agulhas Rings; Holton et al., 2016; Le Bars et al., 2014a; van Sebille et al., 2010). However, they suggest that Agulhas Rings do not account for all of the Agulhas Leakage and hypothesize that smaller-scale features such as submesoscale eddies and jets play a role in Agulhas Leakage. Several studies have also, at least partly, relied on satellite altimetry to investigate the structure and variability of the Agulhas Current (Beal et al., 2015; Krug & Tournadre, 2012; Krug et al., 2014; Le Bars et al., 2014b; Rouault et al., 2010).

At present, ocean models are advanced enough to reproduce key elements of the Agulhas Current System such as the Agulhas Retroflection and Agulhas Ring shedding. However, recurrent model biases, such as upstream retroflection of the Agulhas Current and Agulhas Rings following a straight, northwestward path into the South Atlantic Ocean (Penven et al., 2011), have hindered our understanding of the evolution of the inshore front of the Agulhas Current. This, in turn, has prevented the development of higher-resolution model simulations that can realistically resolve the Agulhas Current's inshore front and topography interaction.

Broadly speaking, it is known from theory and observations that inshore of the core of the Agulhas Current, vorticity is cyclonic (due to interaction with the bathymetry), while offshore of the core, vorticity is anticyclonic (Beal et al., 2006; de Ruijter et al., 1999). However, when considering the energetic, eddying nature of the current, features such as large mesoscale meanders can have significant effects on the vorticity dynamics (e.g., Tsugawa & Hasumi, 2010). As such, and considering the dominance of the meander mode in the variability of the Agulhas Current, it is useful to divide the current into meandering and nonmeandering modes when trying to unravel its dynamics (Malan et al., 2018).

Use of synthetic Lagrangian particles is an increasingly popular technique for the diagnosis of ocean dynamics, especially in complex systems (van Sebille et al., 2018) and has been used with significant success in the Agulhas Current system for quantifying Agulhas Leakage (Doglioli et al., 2006; Durgadoo et al., 2013; Loveday et al., 2014; van Sebille, Biastoch, et al., 2009; van Sebille, Barron, et al., 2009). van Sebille, Biastoch, et al. (2009) used a model to show that particles inshore (offshore) of the core are more likely to leak into the South Atlantic Ocean (flow back into the Indian Ocean via the Agulhas Return Current). Furthermore, Blanke et al. (2009) suggested that particles on the Agulhas Bank will leak into the South Atlantic Ocean through different paths depending on their distance from the coast; that is, particles closer to the coast will follow the coast into the South Atlantic Ocean, while particles further offshore will enter the South Atlantic Ocean through the Southern Benguela before being advected further offshore. However, the mechanism by which water from the main Agulhas Current is connected to the "leaky" water on the Agulhas Bank remains unknown, as does its connection to the turbulent, mesoscale, offshore pathway of Agulhas Rings contributing to leakage described by Doglioli et al. (2006).

Recently, Lagrangian jet coordinate systems have proved to be a powerful tool in disentangling the variability of energetic western boundary current jets (Delman et al., 2015; Archer et al., 2017, 2018). The more dynamically relevant Lagrangian coordinates are based around the center of the current jet, enabling the analysis of properties of the current jet itself and removing the effect of deviation in the location of the center of the current.

In this paper we use in situ observations to show the potential of quasi-Lagrangian measurements with an investigation into the relationship of the upstream surface velocity configuration and the trajectories

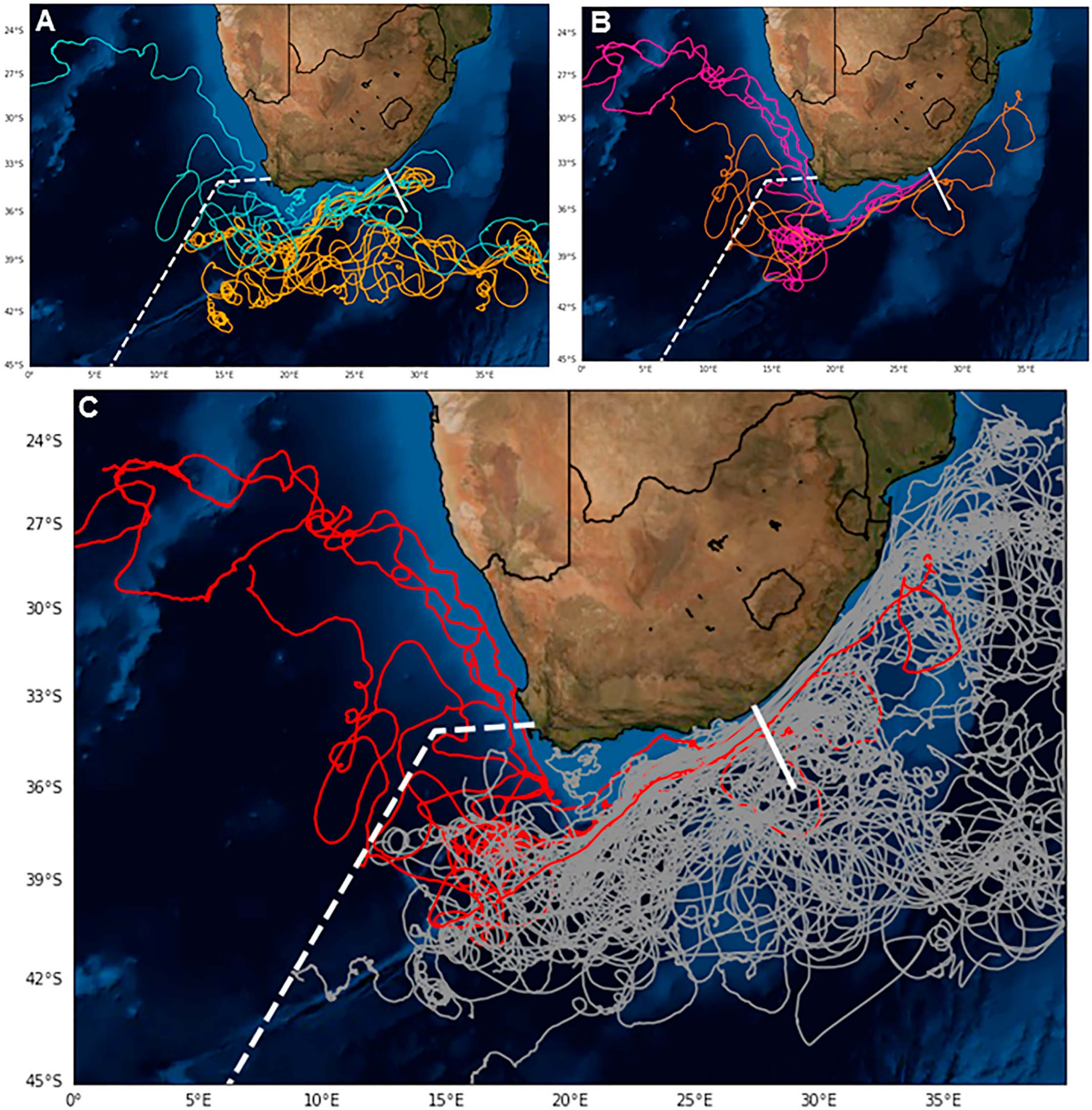

Figure 1. Tracks of all drifters intersecting satellite track #096 (or Agulhas System Climate Array, ASCA) across the Agulhas Current. Orange and blue trajectories (a) represent drifters that were deployed during the ASCA 2015 and 2016 cruises, respectively. Pink and brown trajectories (b) indicated drifters that leaked from inshore and offshore of the Agulhas Current core respectfully. The red trajectories (c) are those of the drifters that leaked into the South Atlantic, while the gray trajectories represent the drifters that remained in the Indian Ocean. The white solid and dashed lines represent ASCA and the Good Hope monitoring lines, respectively. The blue shading represents the bathymetry of the region.

surface drifters follow. Additionally, we use these drifters and ship-based measurements to expose biases in satellite-derived geostrophic velocities in the Agulhas Current.

2. Methods

2.1. Drifter Deployments

Using surface drifters from the Global Drifter Programme, we are able to unambiguously track the movement and variability of the surface currents in the Agulhas region and hence garner information about mechanisms of surface Indian-Atlantic Ocean exchange as per van Sebille, Biastoch, et al. (2009). Surface drifters cannot be considered truly Lagrangian as they only follow surface flow and not isopycnal surfaces; thus, in this study we consider them as quasi-Lagrangian (McDougall, 1987; Swift & Riser, 1994; Zhang et al., 2001). In April 2015 and 2016, 10 and 5 drogued drifters were deployed, respectively, along the Agulhas System Climate Array (ASCA) positioned at 34°S and extending 300 km offshore (Morris et al., 2017; Figure 1). From the 2015 deployments, eight were targeted to regions of high velocity and two were deployed in an offshore anticyclone. Based on mean historical estimates, the 2016 drifter deployment positions were targeted to key frontal locations (i.e., inshore edge, core, offshore edge, and outside; Beal et al., 2015). During both cruises ship acoustic Doppler current profiler (S-ADCP) measurements were collected over the full duration of the cruises. Meteorological constraints limited the 2015 cruise to 180 km offshore while the 2016 cruise extended 270 km offshore. Due to the vessel draft and instrument setup, the first bin of good data was centered at 24 m and is thus classified as the surface bin. The S-ADCP collected data every 2 s, which was averaged into 5-min bins.

2.2. Historical Data

To augment the dedicated drifter deployments discussed above, additional drogued drifters from the global drifter program that intersect the ASCA transect between September 1992 and October 2017 were used for further analysis (Figure 1). Given that the location of the ASCA lies directly under the descending TOPEX/Jason altimeter track #096, along-track absolute dynamic topography could be used to reconstruct the surface velocity structure along the transect (Beal et al., 2015; Morris et al., 2017).

Drifters' positions relative to the core of the Agulhas Current were determined in two steps. First, the drifters were colocated to a satellite overpass using a 5-day threshold (according to Bryden et al., 2005, the Agulhas Current has a decorrelation time scale of 10 days). Using the 14-km resolution, filtered along-track absolute dynamic topography data (produced by AVISO and distributed by Copernicus Marine; SEALEVEL_GLO_PHY_L3_REP_OBSERVATIONS_008_045), cross-track geostrophic velocities were derived using the method described by Le Bars et al. (2014b). These velocities were then matched to the corresponding drifter. Large meanders (or Natal Pulses) are the largest mode of variability in the Agulhas Current (Krug et al., 2014) and significantly change the vorticity structure on the inshore edge of the Agulhas Current during their passage (Malan et al., 2018). Here, the focus is to understand the Agulhas Current in its nonmeandering state; hence, the drifters that crossed the transect during a meander were considered to be outliers and removed from the data set so as not to confuse the signals of these two separate dynamic states. Meandering events are classified by the surface velocity maxima position being greater than 40 km from its mean position (Krug et al., 2014).

As many previous authors have noted, defining leakage in such a highly dynamic region such as the Cape Basin is complicated (Durgadoo et al., 2013; Le Bars et al., 2014b; Loveday et al., 2014). For consistency we will use the Good Hope monitoring line as the Agulhas Leakage reference following Durgadoo et al. (2013) and Loveday et al. (2014).

Between September 1992 and October 2017, 49 drogued drifters (including those deployed on the two ASCA cruises) crossed altimeter track #096 (Figure 1). Five of these drifters leaked from the Agulhas Current into the South Atlantic Ocean (Figure 1b), while the rest remained in the Indian Ocean (gray trajectories in Figure 1c). The drifter trajectories highlight the complexity of the region and give an indication that the analysis of Eulerian observations may filter out or alias much of the variability in the system.

3. Results

3.1. Deployments

The immediate difference between the conditions of the two ASCA cruise deployments is the speed, location, and width of the Agulhas Current (Figure 2). The S-ADCP data extend further inshore during the 2015 cruise

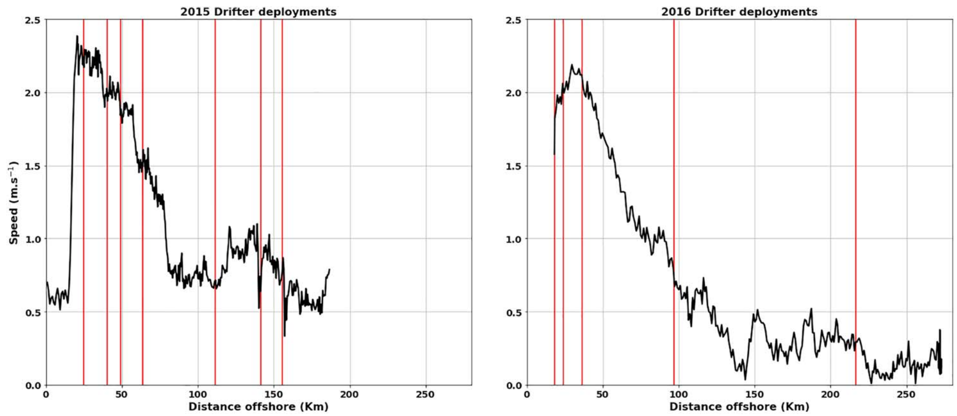

Figure 2. Surface speed from the 2015 (left) and 2016 (right) ship acoustic Doppler current profiler transects. The vertical lines indicate the location of drifter deployments.

showing the high shear inshore of the core of the Agulhas Current. The magnitudes in the core are similar, differing by a maximum of 0.2 m/s (2.4 m/s in 2015 and 2.2 m/s in 2016). However, the overall Agulhas Current surface speeds are faster in 2015 compared to 2016; this is particularly noticeable beyond 100 km offshore. The maximum velocities had shifted approximately 5 km further offshore during the 2016 transect when compared to the 2015 transect. The majority of the drifters during the 2015 transect were deployed at random, offshore of the AC core, while the drifters on the 2016 cruise were deployed in more targeted locations. As a result one drifter was deployed inshore of the Agulhas Current core, while two were deployed in the Agulhas Current core and two offshore of the Agulhas Current core during the 2016 cruise. During the 2015 drifter deployments only one drifter was deployed in the core, while the rest were deployed further offshore, often missing steep velocity gradients.

At the end of their life, the drifters deployed in 2015 were either still in the Agulhas Retroflection or had been advected back into the Indian Ocean. One of the drifters still, in the retrofection, was caught in an eddy (identified by the circular motion of the drifter). The two drifters deployed closest inshore during the 2016 cruise leaked into the South Atlantic. One of the drifters that leaked had a spiral motion as it followed the western Agulhas Bank shelf edge. These loops had radii less than 20 km. The middle most drifter was advected onto the Agulhas Bank before being grounded close to Cape Agulhas. The two drifters deployed furthest offshore remained in the Indian Ocean until the end of the study.

3.2. Geostrophic Current Profiles

As seen in Figure 3a, the geostrophic velocities in the core of the Agulhas Current range between 0.9 to 1.5 m/s. The velocities taper off with increasing distance offshore and a few cross track velocity profiles show an offshore peak situated 100 km from the velocity maxima. On two occasions, velocities of −1 m/s were observed 200 km offshore of the velocity maxima, indicating the presence of a large mesoscale feature. Drifters intersected the transect between 50 km inshore of the velocity maxima and 230 km offshore of the velocity maxima. These drifters has intersect velocities ranging between −1.4 to 2.5 m/s.

Of the 49 drifters, only 16 drifters (32.7%) intersect the transect inshore of the Agulhas Current core, 3 (18.8%) of which leak into the South Atlantic (Figure 3b). These leaked drifters are all in the same position relative to the Agulhas Current core (~20 km inshore of the velocity maxima) when crossing the transect and also propagated at speeds greater than 1.5 m/s. Here the gradient between the surface velocity maxima and the inshore region is not much different from the average. Interestingly, these drifters all crossed the east west section of the Good Hope line (Figure 1b). Two drifters completed several small loops while propagating along the inshore edge of the Agulhas Current, while the third completed several small loops while propagating north westward along the western shelf edge of the Agulhas Bank (as described above). All three of these drifters followed the continental shelf northward.

In the case of the two drifters that leaked into the South Atlantic but intersected the transect 50 km offshore of the Agulhas Current core, an offshore velocity maxima exists 180 km from the core for the one drifter. This offshore velocity maxima is found almost immediately after the velocity minima and is approximately 0.5 m/s greater. This offshore velocity maxima are most likely caused by a persistent cyclonic eddy observed

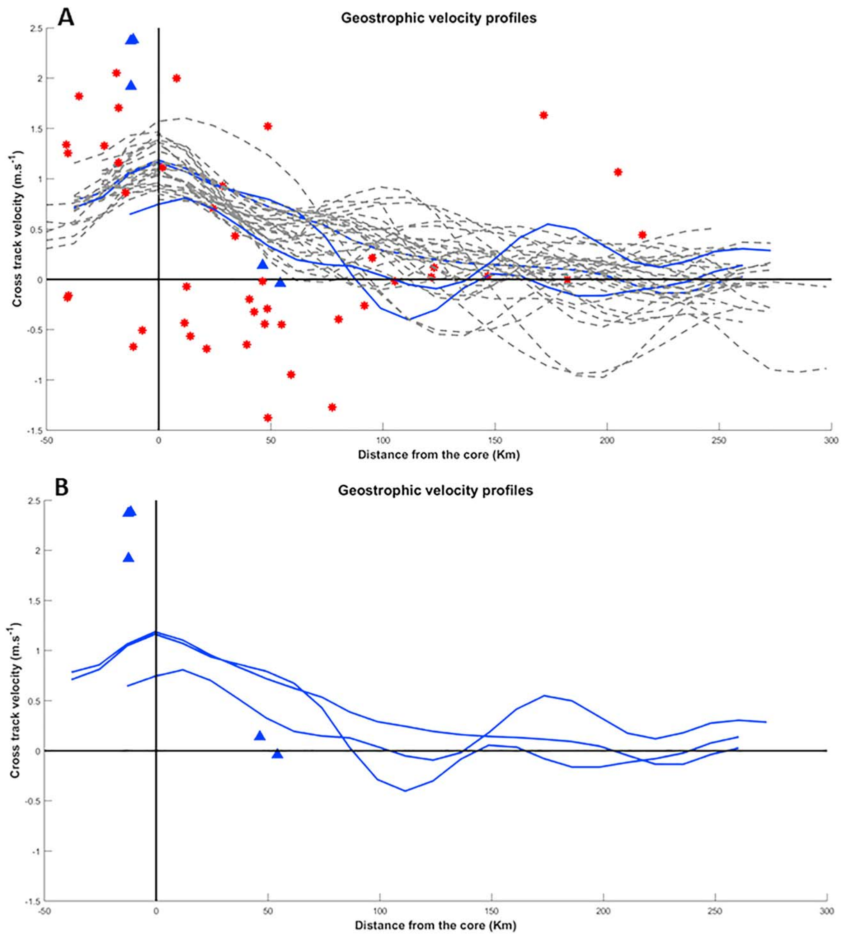

Figure 3. (a) Cross-track surface geostrophic velocity (m/s) relative to the velocity maxima of the Agulhas Current. A positive velocity indicates a southwest direction. The blue triangles (red stars) indicate the position and velocity of the drifters that leaked into the South Atlantic Ocean (remained in the Indian Ocean) crossed the transect. Subplot (b) highlights the cross track geostrophic velocities and drifter velocities for the drifters that leaked into the South Atlantic Ocean.

in satellite observations (not shown). In the case of the second offshore leaked drifter, after the velocity maxima (or Agulhas Current core) the surface velocities taper off with increasing distance offshore. Both of these drifters traveled at relatively low speeds of not more than 0.5 m/s. These drifters intersected the Good Hope line's diagonal section with one following a similar path to the drifters from the inshore side while the other remained in the Cape Basin.

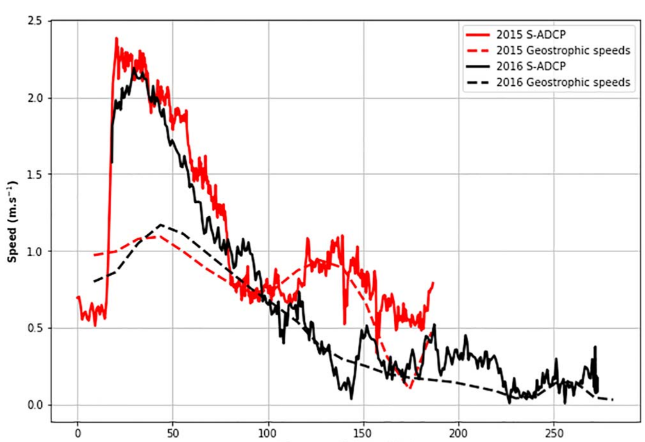

Figure 4. A comparison of the 2015 (red) and 2016 (black) dedicated ship acoustic Doppler current profiler (S-ADCP) transects with the cross-track satellite-derived geostrophic velocities from the same day (dashed).

3.3. S-ADCP Altimetry Comparisons

Altimetry has proven to be a useful tool in tracking the location of the Agulhas Current; here we investigate how representative the cross-track geostrophic profile is of the shear (particularly inshore of the Agulhas Current core; Figure 4). The geostrophic speeds derived from satellite altimetry and S-ADCP speeds follow similar trends. The 2015 transect has a correlation of 0.627, while the 2016 transect has a correlation of 0.92 ($p = 0.01$). Beyond 80 km offshore, the two measurements agree quite well in both 2015 and 2016 with correlation values of 0.813 ($p = 0.008$) and 0.858 ($p = 0.00$), respectively. However, the S-ADCP is able to capture a lot more variability than the satellite measurements closer inshore (particularly in high shear regions). The maximum geostrophic speeds are also offset by a few kilometers when compared to the S-ADCP.

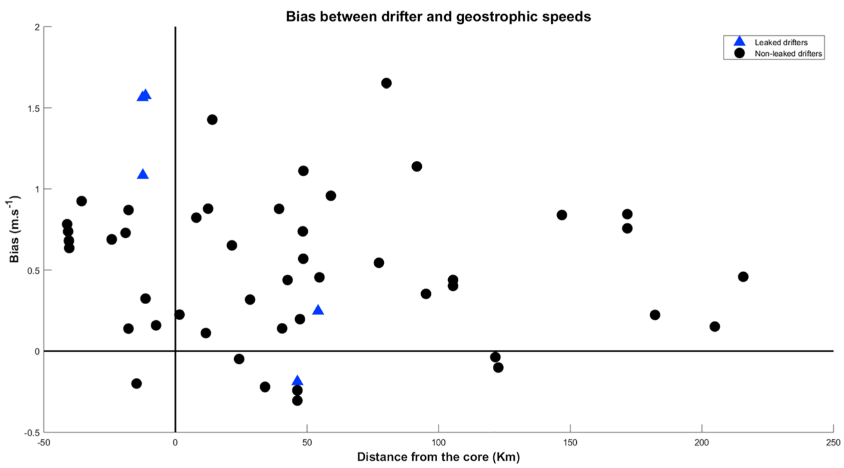

Figure 5. The bias between the drifter intersect velocity and that of the satellite-derived geostrophic velocity. The blue triangles indicate the drifters that leaked into the South Atlantic, while the black dots indicate drifters that remained within the Indian Ocean.

Inshore of 80 km, the magnitudes increase substantially. With this increase, the divergence between the two measurements increases by as much as a factor of two in both 2015 and 2016.

3.4. Drifter Altimetry Comparison

A wide range of variability in the bias between the drifter and geostrophic speeds is apparent, ranging from −0.5 to 1.5 m/s (Figure 5). Drifter speeds and geostrophic speeds have been observed to have a bias as large as 1.4 m/s at the same hydrodynamic location. It is interesting to note that the bias in the case of leaked drifters can be up to 1.6 m/s. As with the S-ADCP and geostrophic speed comparison, the magnitude of the bias between the drifters and the geostrophic speeds tapers off slightly with increasing distance from the core.

The drifter measurements include ageostrophic components of the flow, including the wind-driven Ekman motion. Parameterizations based on wind speed Ralph and Niiler (1999) suggest that Ekman flow here is ~0.08 m/s to the north-northeast (biasing the drifter measurements slightly negative), with values as high as ~0.25 m/s during sustained wind events. These are much smaller than the range of biases seen in Figure 5 indicating that Ekman flow is not the lowest-order explanation of these differences.

4. Discussion

The variability of the Agulhas Current can easily be missed when deploying drifters at fixed geographical locations or at steep surface velocity gradients on the offshore region of the current as seen for the 2015 drifter deployments. Due to strong dynamics in the Agulhas Current (particularly inshore of the core), it is important to have a higher sampling resolution. In an attempt to overcome this, drifter deployments were targeted to key frontal locations during the 2016 cruise. Thus, a jet orientated reference was used to deploy the drifters and target key regions of the Agulhas Current (Figure 2; Delman et al., 2015).

Applying this jet reference frame to historical surface drifter data, we observe that 18.8% of the drifters inshore of the Agulhas Current core (in a nonmeandering state) leak into the South Atlantic (Figure 3). Based on synthetic Lagrangian particles and RAFOS floats, van Sebille et al. (2010) and Richardson (2007) both state that a float or a drifter has a 25% chance of leaking into the South Atlantic (with no reference to the drifter or particles position within the current). Using S-ADCP transects across the Agulhas Current, Beal et al. (2006) show that the inshore section of the Agulhas Current is dominated by cyclonic vorticity. Van Sebille, Biastoch, et al. (2009) go on to show that this cyclonic vorticity may be responsible for a bifurcation of the Agulhas Current in the Agulhas Retroflection region that is responsible for 12% of the Agulhas Leakage. Van Sebille, Biastoch, et al. (2009) also show that a weaker Agulhas Current tends to suppress anticyclonic vorticity, which in turn extends the Agulhas Retroflection further southwest and results in increased Agulhas Leakage. Using this jet reference frame has shown that three of the five drifters that leaked into the South Atlantic were in the same location relative to the core. These drifters were in a region of high shear that has been linked to the generation of submesoscale cyclones (Krug et al., 2017). This supports the idea that smaller cyclonic features play a significant role in Agulhas Leakage; this has been shown by Doglioli et al. (2006) who found that cyclonic looping trajectories are responsible for 17.4% of Agulhas Leakage.

When investigating the bias between the absolute velocities collected by the S-ADCP transect and the drifters with the geostrophic velocities derived from satellite altimetry, we notice an inconsistency in the bias (Figures 4 and 5). This has also been observed by Krug et al. (2014) who showed a 0.35 m/s bias between a moored ADCP and geostrophic speeds. Several factors may contribute to this bias. It is known that altimetry suffers from errors caused by weaknesses in the mean geoid, low-resolution (so the altimetry is unable to capture small-scale features), and nonmesoscale signals (such as internal tides; Dibarboure et al., 2011; Losch & Schröter, 2004; Pujol et al., 2016; Rio et al., 2011). Given surface drifters are used as additional data points in the mean dynamics topography product and the low numbers of surface drifters in the Agulhas Current, this may be an additional source of error (Rio et al., 2011). Additionally, Fratantoni (2001) showed that satellite altimetry is not able to capture the absolute sea level with sufficient accuracy to accurately determine time mean currents. This study goes on to show that the sea level anomaly is unable to account for the ageostrophic component in the variations of currents. Krug et al. (2017) and Rouault et al. (2010) have shown that the Agulhas Current region has a large ageostrophic component in the form of winds, submesoscale eddies, and other features. Beal and Bryden (1999) show that geostrophic velocity profiles do not capture inertial oscillations suggesting they are ageostrophic motions. A combination of the small-scale features and the ageostrophic dynamics may explain a large portion of the bias inshore of the Agulhas Current core seen in Figures 4 and 5. Here the bias for leaked drifters inshore of the speed maxima ranged between 1.1 and 1.5 m/s. These dynamics may play a vital role in the leaking of surface drifters. These results show that in situ observations combined with methods such as those used by Beal et al. (2015) and Krug et al. (2017) are useful for further understanding the dynamics of the Agulhas Current particularly in high shear regions.

How could these submesoscale dynamics impact Agulhas Leakage?
Our results indicate that there may be an optimum upstream velocity maxima that aid in the leaking of surface drifters. We know from literature that cyclonic vorticity aids in the leakage of drifters (or particles) (van Sebille et al., 2010). This cyclonic vorticity is generated by the horizontal shear between the velocity maxima and the inshore boundary of the Agulhas Current. Three of the drifters in our study that leaked into the South Atlantic were in this high shear region before they leaked. They also demonstrated the largest bias between the drifters velocity and the geostrophic velocity. The cyclonic vorticity in this high shear region may aid in steering the drifters closer inshore until they end up in an ideal location for leaking in to the South Atlantic (Blanke et al., 2009). Van Sebille, Biastoch, et al. (2009) show that even though a weaker Agulhas Current has less inertia, it detaches from the continental shelf further downstream as such a weaker Agulhas Current leads to increased Agulhas Leakage by suppressing anticyclonic vorticity. However, when the upstream velocity is strong the anticyclonic vorticity is so intense it acts as a potential vorticity barrier to mixing (Beal et al., 2006).

5. Conclusion

It is becoming increasingly important to ensure freely floating instrumentation (such as Argo floats and surface drifters) remain in or propagate toward undersampled regions such as the South Indian and South Atlantic Oceans. Targeting drifter deployments to specific dynamics (such as shear edge features, which may have a large dynamic importance relative to their relatively small geographical area) will substantially increase our understanding of these features and in turn will increase the value of drifter observations. In aiming to observe dynamics of the inshore velocity front and Agulhas Leakage by means of surface drifters, we find targeting deployments according to a jet reference frame, rather than the traditional fixed geographic one, to be highly useful. In this way, the likelihood of sampling the region where water leaks from the Agulhas Current into the south Atlantic Ocean is increased. Biases between geostrophic velocities and absolute velocities have indicated that surface drifters are more likely to leak from inshore of the Agulhas Current core in a region of high shear. However, the bias between these velocities is inconsistent, with the highest range in bias inshore of the Agulhas Current core. These inconsistencies may be linked to several factors including, ageostrophic processes, small-scale dynamics, and error in the mean dynamics topography and geiod. Augmenting these data sets with more high-resolution observations such as surface drifters, land-based high-frequency radar, and synthetic aperture radar imagery will substantially improve our understanding of the dynamics involved in Agulhas Leakage.

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