MEASURING SURFACE CURRENT VELOCITIES IN THE AGULHAS REGION WITH ASAR

Marjolaine J. Rouault[1], **A. Mouche**[2], **F. Collard**[2], **J. A. Johannessen**[3], **and B. Chapron**[4]

[1]*Ecosystem Earth Observation, CSIR, 7700 Rosebank, South Africa*
[2]*Direction of Radar Applications, CLS, Plouzané, France*
[3]*NERSC, Bergen, Norway*
[4]*IFREMER, Plouzané, France*

ABSTRACT

Surface current information collected over the Agulhas Current region and derived from the Doppler centroid anomalies of the Advanced Synthetic Aperture Radar (ASAR) are examined. The sources of errors and potential use of the radar surface velocities for oceanographic research in the Agulhas Current are assessed. Comparisons between radar, altimetry and surface drifters observations of the surface currents show that accurate wind fields are a strong pre-requisite to the derivation of meaningful surface current velocities from ASAR images. Innacurate wind fields induce a strong bias between the observed and radar derived surface current velocities, particularly over regions where the radar incidence angle is less than 30^o. Time averaged maps of the surface radial velocities show that at large radar incidence angles, the ASAR derived velocities are able to represent the mean position and intensity of the Agulhas Current with striking accuracy. The quasi-instantaneous nature of radar acquisitions in WSM images combined to the relatively high resolution of the surface current radial velocity allow synoptic maps of the Agulhas Current core to be produced for the first time. The ability of the SAR to represent the mean circulation in the Agulhas Current proper and to capture the sub-mesoscale variability along the Agulhas Banks far exceeds that of merged altimetry measurements.

Key words: Agulhas Current, radar surface current velocities, Doppler shift method, current variability.

1. INTRODUCTION

The Agulhas Current provides a ideal natural laboratory for testing new remote sensing products such as the ASAR surface current radial velocities. With a mean transport of about 70 Sverdrup and surface current speeds at times greater than 2 m.s^{-1}, the Agulhas Current constitutes the strongest western boundary current in the southern hemisphere [1]. Since July 2007, maps of surface current radial velocities in the Agulhas Current region have been systematically recovered from the Doppler shift measurements of the Advanced Synthetic Aperture Radar (ASAR) under the ESA funded SAR ocean wind-wave-current project ([2]; [3]). The surface current radial velocities derived from the ASAR instrument provide a completely new type of information to the scientific community and offer a unique opportunity to further our understanding of the Agulhas Current system, particularly in regions where other remote sensing technique might be challenged by factors such as land contamination, cloud coverage, isothermal flows or strong ageostrophic flows. This study assesses illustrates how radar derived surface current velocities can complement other remote sensing techniques to better portray the highly complex and variable dynamics of the Agulhas Current circulation. The data and method used in this study are described in Section 2. In Section 3, surface current information derived from the altimetry and the ASAR dataset are compared against lagrangian drifter observations. In Section 3, the ability of both the merged altimetry and the radar velocities to represent the instantaneous and time-averaged circulation of the Agulhas Current system is addressed. The ASAR radial surface current velocities are used in combinations with the high resolution sea surface temperature measurements from Seviri to better characterise the variability of the Agulhas Current. The conclusions of this study are drawn out in Section 4.

2. DATA AND METHOD

Radar surface current velocities are derived from Wide Swath Medium resolution images (WSM) obtained from the Advanced Synthetic Aperture Radar (ASAR) instrument onboard Envisat. Each ASAR WSM image covers an area on the ground of about 400 km by 400 km. Over the Agulhas Current region, one descending (morning) and one ascending (evening) ASAR WSM image has been obtained every 3.5 days since July 2007. The ASAR WSM images are processed by the radar division of CLS (Collect Localisation Satellites) to produce a surface current radial velocity map, still subject to validation. The

ASAR radial velocity provides a measure of the absolute surface current velocity in the line of sight of the radar, with positive values indicating a flow moving away from the radar. The ASAR radial velocity product has a resolution of about 4 km in range and 8 km in azimuth [2]. Near real time surface current radial velocities derived from ASAR are freely available for download on the soprano website (http://soprano.cls.fr). The methodology used to derive surface current information from ASAR was pioneered by Chapron [4] and can be summarised as a 3 steps process: 1) calculating the Doppler anomaly by removing the relative motion of the satellite to the earth, 2) removing the influence of the wind from the total Doppler anomaly centroid and 3) converting the Doppler anomalies to radial velocities. The Doppler anomalies are corrected for large along-track cross section variations and remaining biases are further removed using land surface references. For each ASAR scenes, ECMWF re-analysis winds are used in combination with the CDOP neural model network of [2], to predict the wind induced contribution to the Doppler anomaly centroid. The predicted wind induced Doppler anomalies are then removed from the total Doppler anomaly centroid to calculate the surface current radial velocities. In this paper, a total of 463 ascending and 358 descending ASAR WSM images collected between the 2^{nd} August 2007 and the 10^{th} of September 2009 were used.

The altimetry product used in this study is the AVISO NRT-MADT product distributed by Ssalto/Duacs and processed by CLS. It consists in a merged dataset of the latest high-quality data produced from the OSTM/Jason-2, Jason-1 and Envisat altimeters and has a spatial resolution of 1/3^o. The AVISO NRT-MADT product uses the mean dynamic topography developped by Rio [5]. The NRT-MADT product is the only dataset available which allows direct comparison between the synoptic circulation captured with the altimeters and the SAR over the length of the ASAR dataset. However the synoptic representation of the surface circulation as shown in the AVISO dataset is compromised by the spatial and temporal interpolation required to merge data from multiple altimeters. The altimetry also differs from the SAR based observations in that it provides an indirect (geostrophy-based) measurement of the surface flow.

Surface lagrangian drifter data processed in real time mode by the Coriolis data assembly center (www.coriolis.eu.org/cdc/tsg_and_buoy_data.htm) are used to validate both the ASAR and AVISO surface current radial velocities. The lagrangian drifters are surface floats equipped with a holey-sock drogue centered at 15 m. The data collected from such drifters are routinely processed and quality controlled by dedicated data assembly centers. Details of the quality control procedure for the real time drifter buoys can be found in the Argo data manual. Two drifter platforms (no 33681 and 14928) were co-located with the ASAR and AVISO dataset. The criterion for the collocation of the drifter and the ASAR dataset was to retain all drifter data collected within 12 hours of the ASAR image acquisition and then to identify the drifters closest to the ASAR data points within a 5 km radius. For the drifters and the AVISO collocations, all drifter observations gathered on the same day as the AVISO daily product are selected. Due to the lower resolution of the AVISO dataset (1/3^o), a search radius of 25 km is imposed to locate the AVISO points located closest to the drifter.

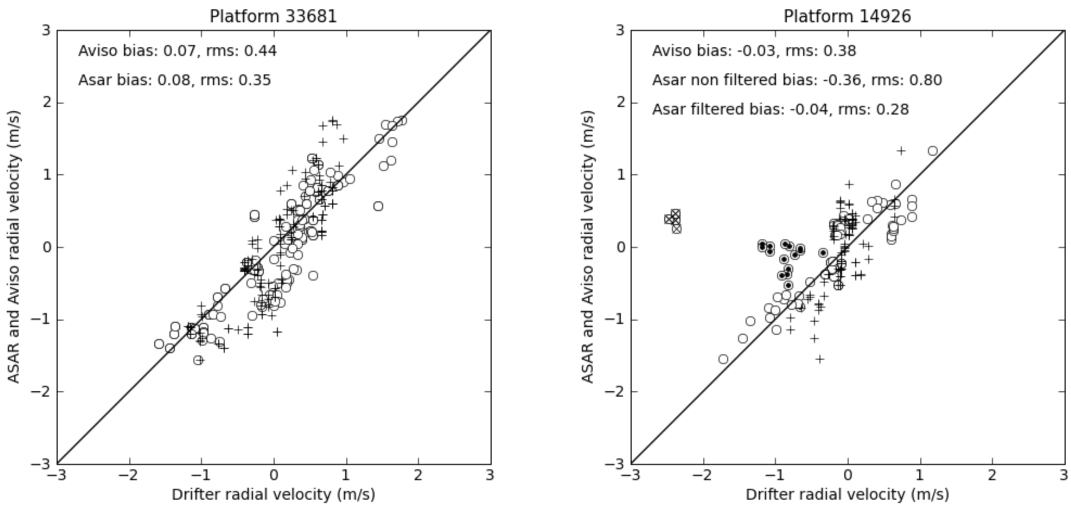
The sea surface temperature (SST) data used in this study is collected from the Seviri instrument onboard the Meteosat Second Generation satellite. It is processed by the French ERS Processing and Archiving Facility (CERSAT) and contains the best hourly SST data available. All analysis were undertaken using the de-clouded SST with no additional flags applied.

3. RESULTS

3.1. Comparisons between ASAR, AVISO and drifter surface radial velocities

Two drifters (no.14926 and no.33681) are selected to compare the ability of the ASAR and AVISO dataset to represent the observed flow and to illustrate the main sources of discrepancies.

Comparisons made with drifter no.33681 and represented in Figure 1a, show that the AVISO and ASAR surface current radial velocities are in close agreement with those recorded by the drifters, with both ASAR and AVISO velocities displaying comparable values for the mean bias and rms error. The main difference lies in the apparent ability of the ASAR derived velocities to capture the stronger currents. In this particular instance, the AVISO dataset is not able to capture flow with radial velocities in excess of 1.17 m.s^{-1}, while the SAR and the drifters both show measured radial velocities reaching above 1.7 m.s^{-1}. The ability of the radar to capture stronger currents is also apparent in comparisons made with drifter no.14926 (Figure 1b). With drifter no.14926 however, the initial bias and rms error associated with the ASAR velocities are large due to a few erroneous data points. A careful manual examination of the ASAR images used in the drifter no.14926 analysis shows that some of the errors in the ASAR velocities can be attributed to large rain cells being present at 3 of the collocated data points. Those points are plotted as crossed-filled circles in Figure 1b. Rain cells can affect the sea surface roughness in many different ways [6]. In this case, the downward draft associated with the rain cells caused local increases in the winds at the leading edge of the rain cell [7]. The processing of the ASAR radial velocities described in Section 2, involves the use of global ECMWF wind fields to remove the influence of the winds on the total Doppler anomaly. Current global atmospheric model do not account for the small and localized impact of rain cells on the atmospheric circulation. Consequently, at the edges of the rain cells, the predicted Doppler shift associated with the ECMWF winds is under-estimated and the resulting surface radial velocities are over-estimated.



(a) (b)

Figure 1. The upper two panels show comparisons between ASAR, AVISO and drifter surface current radial velocities (in m.s^{-1}) for drifter no.33681 (a) and drifter no.14926 (b). AVISO velocities are plotted as crosses while ASAR velocities are plotted with white circles. Circles containing a cross indicate ASAR data points flagged due to large rain cells being present, while circles containing dots indicate ASAR data points flagged due to wind induced bias at low incidence angle (less than 30^o). Flagged data points have not been included in the calculation of the mean and bias.

The second source of error is linked to poor wind corrections applied at low radar incidence angles. These particular data points appear as dot-filled circles in Figure 1b. In the CDOP neural network model mentioned in Section 2, Collard et al. [2] show that at low incidence angles, the returned radar echoes are stronger and dominated by larger and faster roughness elements, so that the relative impact of the wind on the Doppler anomaly increases with decreasing incidence angle. Due to the inverse relationship between the required wind correction on the Doppler anomaly and the radar incidence angle, more errors in the predicted radial velocity of the current are therefore expected at low incidence angles. The impact of poor wind corrections applied to datapoints with low incidence angles on the ASAR surface current radial velocity dataset is illustrated in Figure 2. Over the whole study region, deviations from the mean radial velocity are for most data points confined within 1 m.s^{-1}, with few data points showing deviation from the mean in excess of 2 m.s^{-1}. For incidence angle below 30^o however, the ASAR radial velocity bias strongly increases, with deviations from the mean sometimes in excess of 4 m.s^{-1}.

One of the main advantage of the ASAR derived velocities over those obtained from AVISO lies in the radar's ability to detect the stronger flows. Merging and interpolation techniques required to map out the geostrophic circulation from altimetry measurements act to suppress regions of strong flow. The use of a smooth geoid grid to derive absolute geostrophic currents also inhibits the detection of intense currents from altimetry. In our comparisons between the altimetry, radar and drifter datasets, the maximum radial velocities derived from AVISO reached about 1 m.s^{-1} while both drifter and radar observations indicated that intense flow with associated radial velocities in excess of 2 m.s^{-1} occured. It is also worth noting that most of the drifter data used for our comparisons are acquired away from the Agulhas Current proper, in regions of the open ocean where altimetry is known to perform well. Although radial velocities derived from ASAR are on occasion able to represent the measured flow with incredible accuracy, the overall performance of the ASAR radial velocity product is negatively impacted by a few very large errors, which appear to be caused by poor wind corrections applied at low radar incidence angles.

3.2. Capturing the time-averaged circulation with ASAR

Current velocities averaged over all ASAR ascending paths observations collected between August 2007 and September 2009 (Figure 3) were used to illustrate the potential of ASAR surface current radial velocity measurements to portray the mean dynamics of the Agulhas Current. In an ascending path situation, the radial velocities extracted from the radar images are roughly aligned with the main direction of propagation of the Agulhas Current and should therefore closely approximate the absolute speed of the Agulhas surface current.

Maps of averaged surface current radial velocities computed for an ascending path configuration using both the ASAR and AVISO datasets (Figure 3), show that the mean position of the Agulhas current, the position of its southern extension and the location of the Agulhas Return currents as represented by the AVISO product, agree

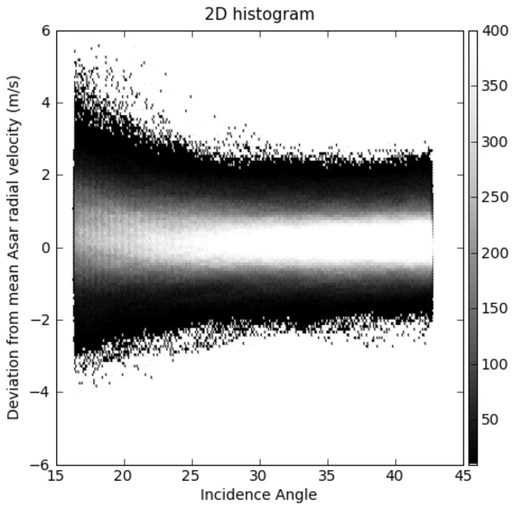


Figure 2. Two-dimensional histogram showing the relationship between the radar incidence angle and the deviation from the ASAR radial velocity mean computed over the study domain. A larger number of errors is seen at lower incidence angles.

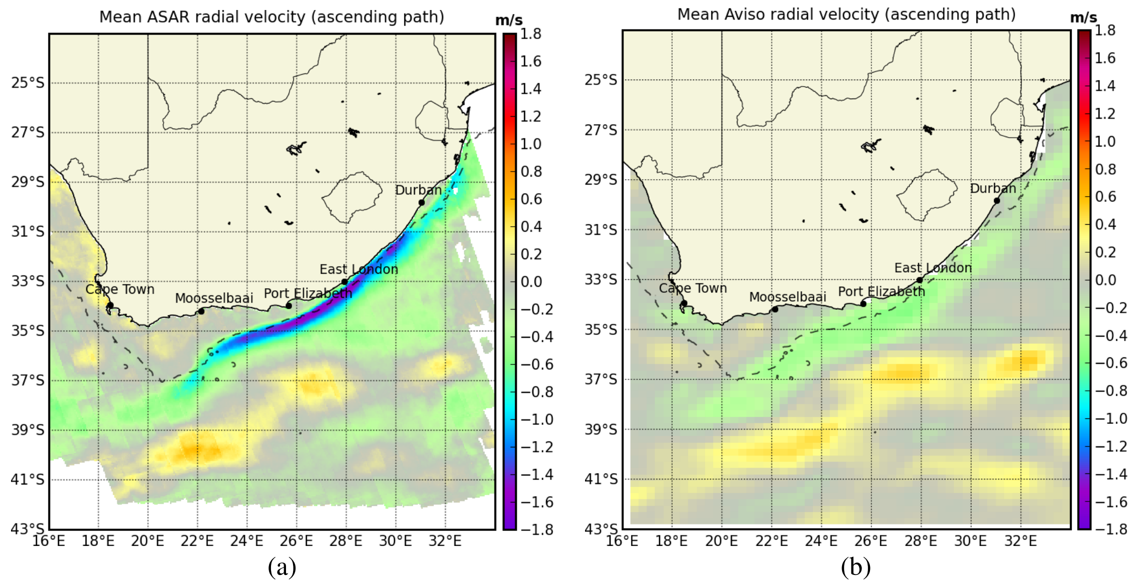


Figure 3. Mean surface current radial velocity (in $m.s^{-1}$) in an ascending path configuration for ASAR (a) and AVISO (b). Positive values (yellow and red) indicate a flow towards the north-east, about 75^o from North. The ASAR mean was computed from 463 ASAR images collected over the Agulhas Current region, from the 2nd August 2007 to the 10th September 2009. Only data points with more than 10 observations and a radar incidence angle greater than 30^o were included in the calculation of the ASAR mean. AVISO current vectors were rotated by the ASAR track angle for each ASAR acquisition to simulate an ascending path situation.

well with those derived from ASAR. The main region of discrepancy lies in the Agulhas Current proper. In the core of the Agulhas Current, the mean surface current radial velocities derived from ASAR are equal to 1.53 m.s^{-1} near East London and 1.49 m.s^{-1} near Port Elizabeth. By comparisons, the mean surface current radial velocities calculated from the AVISO dataset at East London and Port Elizabeth only reach 0.53 m.s^{-1} and 0.58 m.s^{-1}, respectively. Away from the Agulhas Current proper, the surface current velocities derived from ASAR and AVISO are similar, with both datasets showing mean radial velocities in the Agulhas Return current of about 0.4 m.s^{-1}.

While the AVISO dataset represents the Agulhas Current as a broad homogeneous flow, the Agulhas Current portrayed with the ASAR velocities appears as a narrow, intense and assymetric current, with the core of the current lying along the shelf break. The properties of the Agulhas Current as portrayed by the SAR are consistent with those derived from hydrographic surveys and remotely sensed SST maps ([8]; [1]). In the northern Agulhas region, the mean position of the Agulhas Current core as seen in the ASAR dataset closely follows the 1000 m isobath, in agreement with that derived from a large number of hydrographic section [9]. The mean radial velocities derived from ASAR corroborate the findings of Pearce and Grundlingh [10], who estimated annual mean current velocities in the northern Agulhas current system to vary between 1.4 m.s^{-1} and 1.6 m.s^{-1} based on ship drift data.

Using a simpler filter to remove ASAR data points associated with low radar incidence angles, we were able to represent the time-averaged circulation of the Agulhas Current with a striking accuracy. The ability of the radar to capture strong and intense flow far exceeds that of the AVISO product in the Agulhas Current proper.

3.3. Capturing the submesoscale eddies with ASAR

Some of the main advantages of synthetic aperture radars over other satellite remote sensing technique is that they are able to image the ocean surface at a high resolution, do not suffer from land contamination and can operate independently of cloud conditions. These characteristics make the SAR a promising sensor to study submesoscale processes (1 to 100 km) and interactions between western boundary currents and the coastal shelf regions.

The SST composite derived over the 27^{th} and 28^{th} of February 2008 imagery provides an intuitive representation of the surface circulation. Surface waters with SST signatures of more than 23^{o}C and plotted in shades of red in Figure 4b, highlight the path of the Agulhas Current, the Agulhas Retroflection (around 16.5E and 41S) as well as the Agulhas Return Current. The southward flowing Agulhas Current which roughly follows the 1000 m depth contour, the retroflection region as well as the circulation associated with the Agulhas Return Current are captured by both the ASAR and the AVISO datasets in Figure 4a.

There is a very good agreement between the patterns of surface circulation displayed in the SST and the ASAR imagery. Large ASAR velocities are associated with strong gradients in SST, and regions of local SST maxima in the Agulhas Current are coincident with the position of the Agulhas Current core depicted by the SAR imagery. The maps of sea surface temperature and ASAR surface current radial velocities both show a widening of the Agulhas Current around 23E, followed by a sharp bend southward at 21E and a subsequent narrowing of the current between 21E and 19E (Figure 4a and Figure 4b). The surface circulation information derived from the merged altimetry dataset is not able to highlight the localised widening or narrowing of the Agulhas Current which was observed at 23E and 21E. A shear edge eddy in formation and centered at 20E can be observed in both the SST and ASAR radial velocity maps. The meander centered at 20E has a well defined SST expression, with a delineated plume of warm Agulhas water originating from the southern edge of the meander seen to loop back towards the current. Based on the SST map in Figure 4b, the circumbscribed cyclonic border eddy measures approximately 80 km by 220 km along the North / South and East / West directions, respectively. This large border eddy is associated with relatively colder water (Figure 4c).

Border eddies such as those captured in the ASAR imagery of the 27^{th} of February 2008 are common features of western boundary currents [11] and their impact on the productivity of coastal shelf waters has been clearly demonstrated [12]. In the Southern Agulhas, the ubiquitous presence of meanders and shear edge perturbations at the inshore edge of the current induces localized upwelling and contributes to the intensification of the thermocline on the Agulhas Bank through the input of warm Agulhas water in the upper layers. Shear edge eddies along the Agulhas Bank also contribute to the transport of cape Anchovy larvae from the spawning ground of the eastern Agulhas Bank to the nursery grounds of South's Africa west coast upwelling system [13]. A proper quantification and understanding of the border shear edge eddies observed in the souther Agulhas Current is necessary to quantify the coastal shelf exchange as well as the inter-ocean transport between the Indian and the Atlantic oceans.

3.4. Tracking the Agulhas Current variability with ASAR and SST imagery

The unique ability of the ASAR radial velocity measurements to image regions of strong flow and shear can be used to sytematically reveal meso-scale features of the Agulhas Current. In a transect taken offshore Port Elizabeth, between 25.6E, -34.05S and 26.6E, -36.5S a gradient method was used to derive the position of the inshore front of the Agulhas Current. The fluctuations in the position of the Agulhas Current inshore front were then computed over the length of the datasets. Strong fluctuations in the Agulhas Current position were used to reveal the

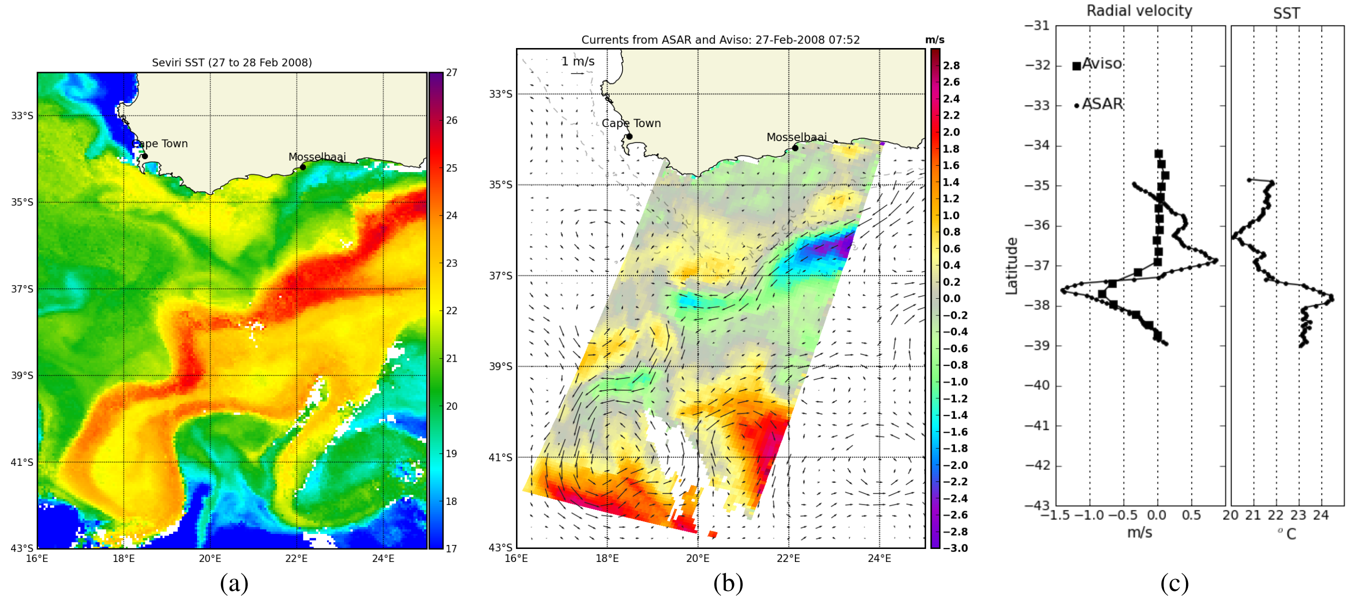


Figure 4. Region of cyclonic shear located inshore of the Agulhas Current at 20E, 37S and evidenced by ASAR and SST datasets. Panel (a) shows an Seviri SST composite from the 27^{th} and 28^{th} of February 2008. In panel (b), color contours of ASAR surface current radial velocities (in $m.s^{-1}$) are plotted for the 27^{th} of February 2008, with positive values (yellow and red) indicating an eastward flow. Overlaid are vectors of AVISO geostrophic currents on that same day. Panel (c) shows a transect of ASAR radial velocity, AVISO radial velocity and SST extracted at 20E.

passage of meanders offshore Port Elizabeth and to derive a better understanding of the drivers of variability within the Agulhas Current. The SST hourly values were averaged into 3 day-moving averages. The SST transect was then extracted and the maximum in SST was defined as the intersection between the overall SST maxima and the local SST maxima over moving windows of 50km within the transect. The largest SST gradient encountered between the computed SST maxima and the coast was then considered to be at the inshore position of the Agulhas Current front. A similar method was applied to the ASAR radial velocity data. The resulting time-series are plotted in Figure 5.

Between August 2007 and September 2009 (Figure 5), two very large anomalies in the Agulhas Current were detected. These large perturbations which occured around August 2008 and April 2009 and persisted for a period of about 1 month offshore Port Elizabeth were identified as Natal Pulses. Natal pulses are large meanders wich are considered to be the main drivers of variability [8] in the Agulhas Current. Fluctuations in the path of the Agulhas Current derived from the ASAR and SST imagery were in good agreement, further validating the ability of the ASAR radial surface velocities to capture the meso-scale variability of the Agulhas Current.

4. CONCLUSION

ASAR observations of surface current radial velocities derived through the innovative use of the Doppler centroid shift provide a new means of imaging the complex upper ocean dynamics of the Agulhas Current region. The quasi-instantaneous nature of radar acquisitions in WSM images combined to the relatively high resolution of the surface current radial velocity measurements allow synoptic maps of the Agulhas Current core to be produced for the first time.

Comparisons between ASAR and drifter derived radial velocities showed that innacuracies in the magnitude of the SAR surface radial current velocities generally occur when erroneous wind fields are used for the removal of the wind induced drift on the overall surface motion. The impact of innacurate wind fields on the quality of the derived surface current fields is particularly pronounced at low radar incidence angles. As a first approach, it was proposed that only radar incidence angles greater than 30^o should be used when computing time-averaged maps of surface current radial velocities. The resulting mean map of surface current radial velocities derived from the ASAR measurements depicted the circulation in the Agulhas Current region with striking accuracy and a high degree of precision. The ability of the SAR to represent the mean circulation in the Agulhas Current proper far exceeded that of the merged altimetry product.

The unique ability of the ASAR radial velocities to accurately position regions of strong flow and shear provides new opportunities for oceanographic research in the Agulhas Current and could lead to a better understanding of the Agulhas Current variability, the formation and development of instabilities in the current and the influence of the Agulhas Current on the shelf regions.

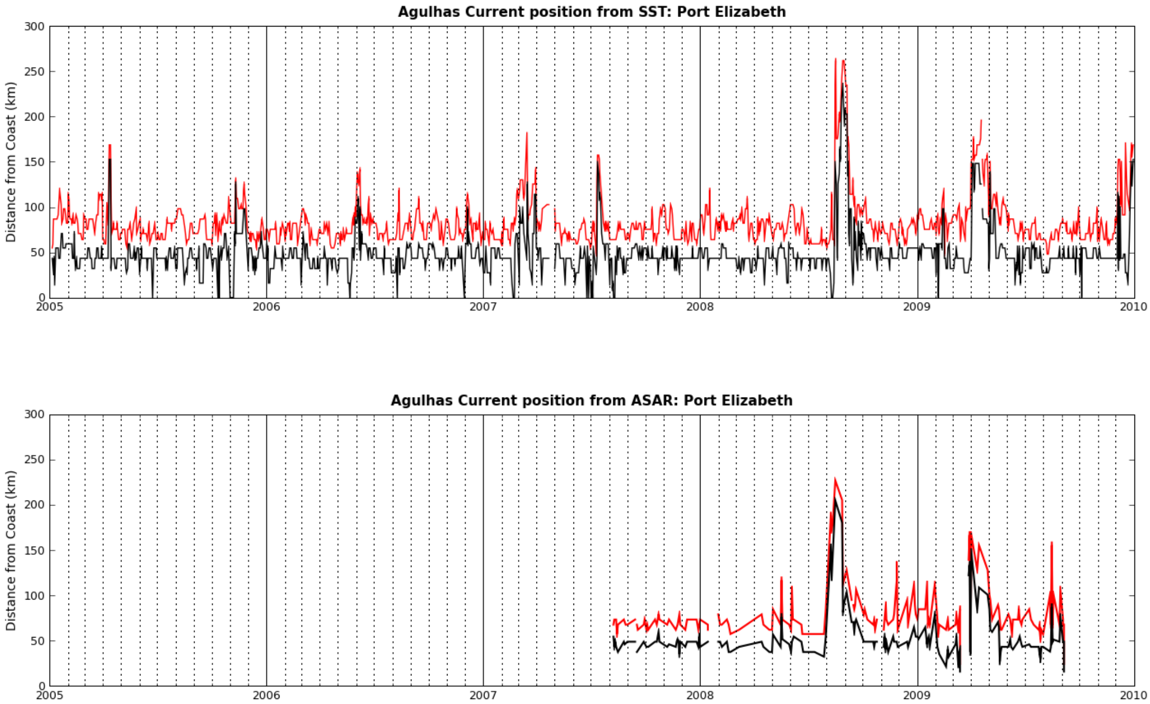


Figure 5. Position of the Agulhas Current core and inshore front detected from the Seviri SST and the ASAR radial velocity datasets. The position of the Agulhas Core is plotted in red while the inshore Agulhas front is plotted as a black line. The upper panel shows the Agulhas Current core and front detected from the Sevri SST dataset. The positions derived from the ASAR radial velocity dataset appear in the lower panel. Large fluctuations in the timeseries are coincident with the passage of Natal pulses.

The availability of accurate wind observations in the Agulhas Current region would greatly improve the accuracy of ASAR radial velocities and could lead to the systematic assimilation of ASAR radial velocities in numerical models or to the routine monitoring of Agulhas transport and variability.

REFERENCES

[1] Lutjeharms, J. R. E. (2006), *The Agulhas Current*, Springer.

[2] Collard, F., A. Mouche, B. Chapron, C. Danilo, and J. A. Johannessen (2008), Routine high resolution observation of selected major surface currents from space, *Proc. of Workshop SEASAR 2008, ESA SP-656*.

[3] Johannessen, J. A., B. Chapron, F. Collard, V. Kudryavtsev, A. Mouche, D. Akimov, and K. F. Dagestad (2008), Direct ocean surface velocity measurements from space: Improved quantitative interpretation of envisat asar observations, *Geophys. Res. Lett.*, *35(L22608)*.

[4] Chapron, B., F. Collard, and V. Kerbaol (2004), Satellite synthetic aperture radar sea surface doppler measurements, *Proc. of the 2nd Workshop on Coastal and Marine Applications of SAR, ESA SP-565*, pp. 133–140.

[5] Rio, M.-H., P. Schaeffer, J.-M. Lemoine, and F. Hernandez (2005), Estimation of the ocean mean dynamic topography through the combination of altimetric data, in-situ measurements and grace geoid: From global to regional studies, in *Proceedings of the GOCINA international workshop, Luxembourg*.

[6] U.S Departement of Commerce, (2004), *Synthetic Aperture Radar Marine User's Manual*, National Oceanic and Atmospheric Administration, Jackson Apel ed.

[7] Atlas, D. (1994), Footprints of storms on the sea: A view from spaceborne synthetic aperture radar, *J. Geophys. Res.*, *99(C4)*, 7961–7969.

[8] Bryden, H. L., L. M. Beal, and L. M. Duncan (2005), Structure and transport of the agulhas current and its temporal variability, *Journal of Oceanography*, *61*, 479–492.

[9] Grundlingh, M. L. (1983), On the course of the agulhas current, *South African Geographical Journal*, *65*(1), 49–57.

[10] Pearce, A. F., and M. L. Grundlingh (1982), Is there a seasonal variation in the agulhas current ?, *Journal of Marine Research*, *40*(1), 177–184.

[11] Koshlyakov, M. N. (1986), *Synoptic eddies in the ocean*, chap. Eddies of western boundary currents, pp. 208–264, D. Reidel Publishing Company.

[12] Lee, T., L. Atkinson, and R. Legeckis (1981), Observations of a gulf stream frontal eddy on the georgia continental shelf, *Deep-Sea Research*, *28*, 347378.

[13] Probyn, T. A., B. Mitchell-Innes, and S. Searson (1995), Primary productivity and nitrogen uptake in the subsurface chlorophyll maximum on the eastern agulhas bank, *Continental Shelf Research*, *15*, 1903192

ACKNOWLEDGMENTS

This study was funded by the Earth Observation Unit of the CSIR. Data was provided by ESA through the study contract no. 18709/05/I-LG.