Agulhas Current Dynamics from Coastal Altimetry

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Abstract. The Agulhas Current (AC) is the western boundary current of the South Indian Ocean and has a crucial role on ocean circulation and climate. In this study AC is observed and characterized by coastal altimetry. Using reprocessed along-track altimeter data with specific data editing and processing strategies, more data can be retrieved near the coast with better spatial coverage and improved quality, compared to standard altimetry datasets. Jason track #96, which crosses the AC nearly orthogonally and on which ACT (Agulhas Current Time-series) array is located has been used in this study to demonstrate our methodology. Altimeter across-track geostrophic current velocity anomalies are derived from the reprocessed Jason-2 along track sea level anomalies from both X-TRACK and ALES processor. These velocities are compared with the ones derived by conventional altimetry RADS (1-Hz) data for both the J-2 track. Time-series of geostrophic surface velocity anomalies (GSVA) every 10 days from Jason #96 are examined. The results indicate the potential usefulness of the along-track altimetry data in contributing to descriptions of surface circulation of western boundary currents and the challenges of such applications on the shelf edge.

Keywords: Agulhas Current, Coastal Altimetry, Satellite Oceanography.

1. Introduction
1.1 Background on the area
The project aims at advancing the understanding of the dynamics of the inshore edge of the Agulhas Current and its mesoscale variability from coastal altimetry.
1.1.1. Agulhas Current
The Agulhas Current (AC) is one of the world's western boundary currents located in the South West Indian Ocean. It flows poleward along the east coast of South Africa from 27°S to 40°S (Figure 1). Between Delagoa Bay (at Maputo) in the north and Port Elizabeth city in the south (Figure 1), the continental shelf is very narrow and never exceeds 25km between the coast and the 200m isobaths [*Lutjeharms*, 2006]. Its path is very narrow and very close to the continental shelf (Figure 1). The continental slope is very steep which gives great stability to the current, not experiencing wide meandering like other western boundary currents. At the surface, it can reach maximum speeds of 2m/s [*Boebel et al.*, 1998]. It is characterized by strong lateral velocity gradients and a central warm core of speeds higher than 1m/s [*Pearce*, 1977; *Pearce and Grundlingh*, 1982]. Its width varies from 50 to 150km with a density structure with isopycnals sloping steeply towards the coast [*Bryden et al.*, 2005; *Casal et al.*, 2009].

The main source of variability in the AC is due to the irregular presence of big meanders that originate from Natal Bight called Natal Pulses. These meanders can cause the offshore displacement of the AC with downstream consequences on the ring shedding and the Agulhas Leakage. Once the AC reaches the southern tip of the African continent, it flows west as it becomes a free jet, before it retroflects back to the Indian Ocean.

AC waters that flow eastward back into the Indian Ocean constitute the Agulhas Return Current (ARC). It flows between 38°S and 40°S (Figure 1) and it experiences very high mesoscale variability [*Lutjeharms and Ansorge*, 2001]. The Agulhas Undercurrent flows as a deep countercurrent beneath the AC, and it could be important for the thermohaline circulation, acting as a ventilation route of the deep Indian Ocean [*Beal*, 2009; *Beal and Bryden*, 1997].
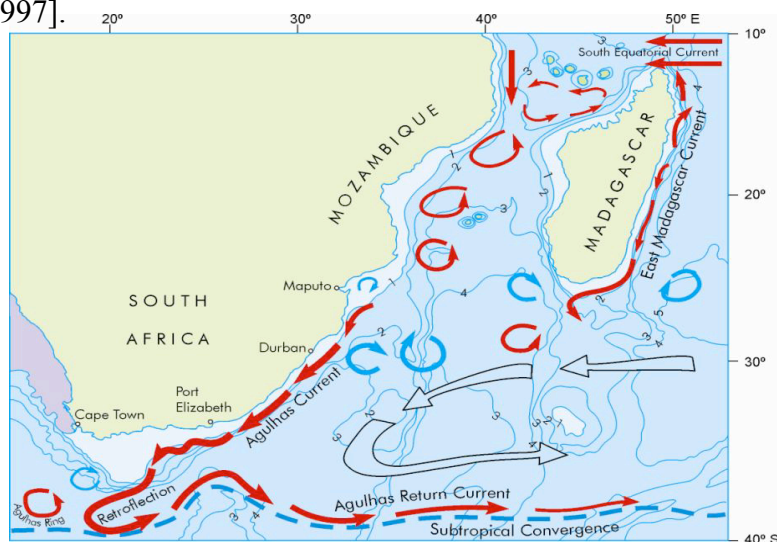
Figure 1. Conceptual portrayal of the flow patterns in the greater Agulhas system. [*Ansorge and Lutjeharms*, 2005]
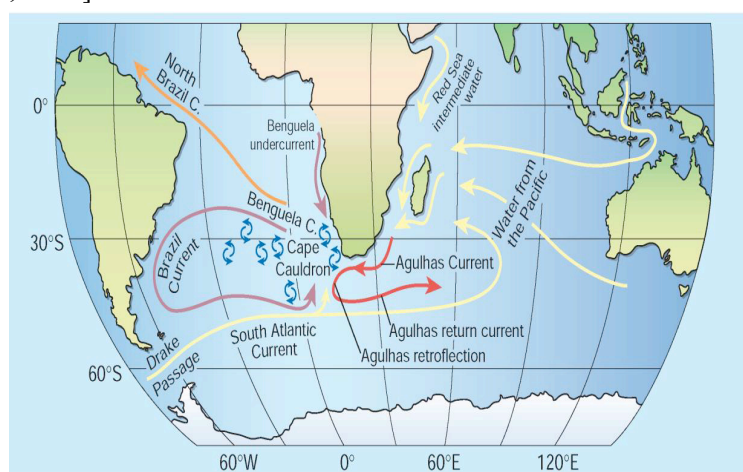
Figure 2. The Agulhas system into the large-scale circulation. [*Gordon,* 2003]

The retroflection of the AC back to the Indian Ocean is unstable and periodically sheds Agulhas rings, eddies, and filaments [*Boebel et al.*, 2003]. In that way, warm and salty Indian Ocean waters find their way into the Atlantic. This advection of the Agulhas rings has significant consequences to the heat and freshwater budgets of the Atlantic Ocean. It thus plays a crucial role in the global thermohaline circulation (Figure 2) and in the climate mechanisms, by providing two thirds of the upper branch of the Atlantic Meridional Overturning Circulation (AMOC) [*Weijer et al.*, 1999].

1.1.2. Importance of Agulhas Current
Ocean climate models and palaeoceanographic studies suggest that the AC and its interoceanic leakage have a crucial role in ocean dynamics and global climate change while the variations in the strength of the leakage may have triggered the end of ice ages, as well as affecting short-term climate variability [*Weijer et al.*, 1999; *Weijer et al.*, 2002]. Studies, such

as [*Rouault et al.*, 2009; *Rouault et al.*, 2010b] have suggested that the Agulhas system is warming thus the Agulhas leakage is increasing mainly due to poleward shift of Southern Hemisphere westerlies linked to the anthropogenic forcing [*Cai*, 2006]. More leakage would accelerate the AMOC and would represent a positive feedback on climate change [*Beal et al.*, 2011]. The increased temperatures would subsequently decrease the global ice volume. However, these findings remain uncertain and highlight the importance of further studies to better understand and assess the role of the AC in the ocean circulation and the global climate.

In response to the need for new observations and monitoring efforts, a number of major programs are currently investigating the AC system. More information on these initiatives can be found in [*Lutjeharms and Bornman*, 2010] and [*Beal et al.*, 2011]. Better understanding the variability of the AC is a vital component of climate change science.

2. Data and Methodology

Different remote sensing data can be used to observe the AC dynamics. As the AC flows close to the continental shelf (as described earlier), usual remote sensing techniques can't be used to monitor this current as they are not only contaminated by the land but also due to cloud coverage, isothermal flows or strong ageostrophic flows.

Altimetry has been proven to be a successful satellite technique that provides a direct quantitative measurement of the ocean circulation. Agulhas Current (AC) flows down the east coast of Africa, closely following the continental shelf, where conventional altimetry is insufficient. Using reprocessed along-track altimeter data with specific data editing and processing strategies, more data can be retrieved near the coast with better spatial coverage and improved quality, compared to standard altimetry datasets.

The coastal altimetry data used in this analysis are the ALES Sea Level Anomalies (SLA), a 20Hz retracked product [*Passaro et al*, 2014] and X-TRACK (CTOH/LEGOS) SLA 1Hz non-retracked product [*Roblou et al.*, 2010], along five tracks (248, 172, 096, 020, 198) that are almost perpendicular to the AC (Figure 3). Other datasets used for this analysis are Daily L4 Operational Sea Surface Temperature (SST) and Sea Ice Analysis (OSTIA), GHRSST product, Mean Dynamic Topography (MDT) for calculating the absolute currents and Bathymetry (ETOPO2 with a grid cell of 10min) for visual purposes.

As satellite altimetry only allows determination of cross-track velocities, this configuration will capture the major component along the AC flow. I have decided to use the year 2010 to make the results comparable to data from the cruise data of the Agulhas Current Timeseries (ACT) for future work. I use these five tracks to track mesoscale features as they propagate down the AC. Time-series of geostrophic surface velocity anomalies (GSVA) every 10 days have been derived:

$$Vs = -\frac{g}{f}\frac{dSLA}{dx}$$,

where **Vs**: across-track component of the geostrophic velocity measured positive to the right of the track direction**, f** is the Coriolis parameter**, g** is the acceleration due to gravity and **dx** is the along-track distance between two adjacent points.

Use of an optimal difference operator that in a single operation both optimally reduces the white noise of the SLA and computes the derivative when computing Sea Surface Height (SSH) slope [*Powell and Leben*, 2004].

$$\Delta_{Nt}^{pq} = \sum_{\substack{n=-p \\ n\neq 0}}^{q} c_n \left(\frac{h_{i+n} - h_i}{n\Delta t}\right),$$

where **hi** is the SLA at the current point (i) along the track, **dt** the sampling interval in seconds, **p and q** the number of points before and

after the current point, **N=p+q**, and, **cn** the weighting coefficients that optimally minimize the

$$\sum_{\substack{n=-p \\ n \neq 0}}^{q} c_n = 1.$$

noise in the slope calculation and satisfy:

For absolute velocities, SLA is replaced by Absolute Dynamic Topography (ADT) by adding MDT to SLA.
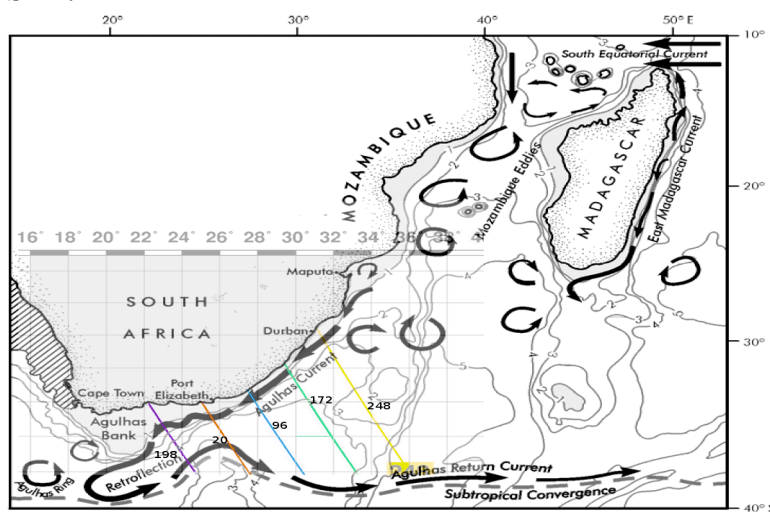

Figure 3. Jason-2 five selected tracks [*Dufau et al.*, 2012].

3. Results and Discussion
3.1 Across-Track Surface Current Velocity Structures

In Figure 4, it is apparent that the filter removes all the noise while it keeps some smaller scales variability. The filter is allowing velocity calculations wherever SLA values exist and it shows to resolving the expected current structures near the coast in a realistic manner. AC meanders are characterized by low SSH and northeastward velocities.
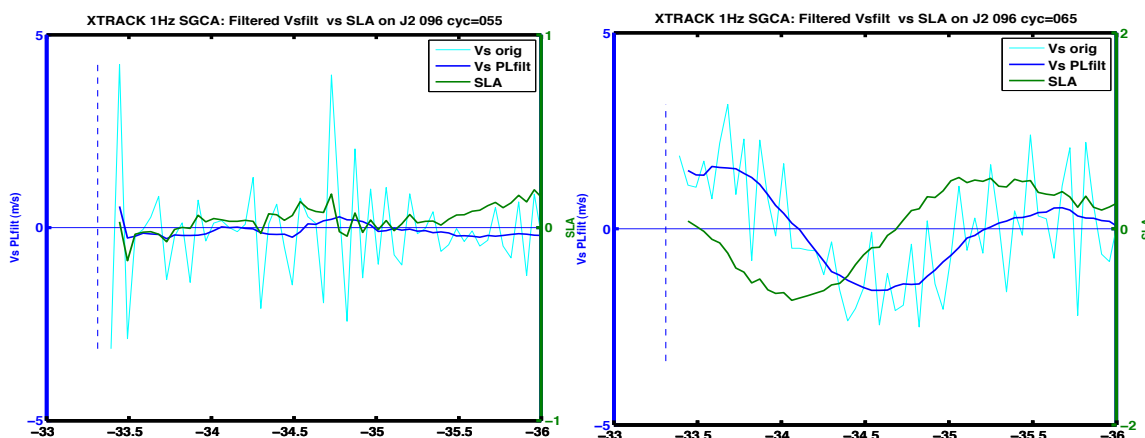

Figure 4. XTRACK 1Hz optimally filtered velocity anomalies (dark blue) versus SLA (dark green) on J2 p096 for a non-meandering current (left) and a meandering current (right). In the background the original velocities (from unfiltered SLA) are shown in cyan.

3.2 Impact of MDT on absolute velocities

Careful selection of MDT is needed since even two well-established MDT models can give very different results in the derived absolute currents. In Figure 5, the DTU10 mean current (left plot) is much smoother and wider than in-situ observations have shown while the

CLS09 mean current (right plot) appears more representative of mean AC as well as more realistic.
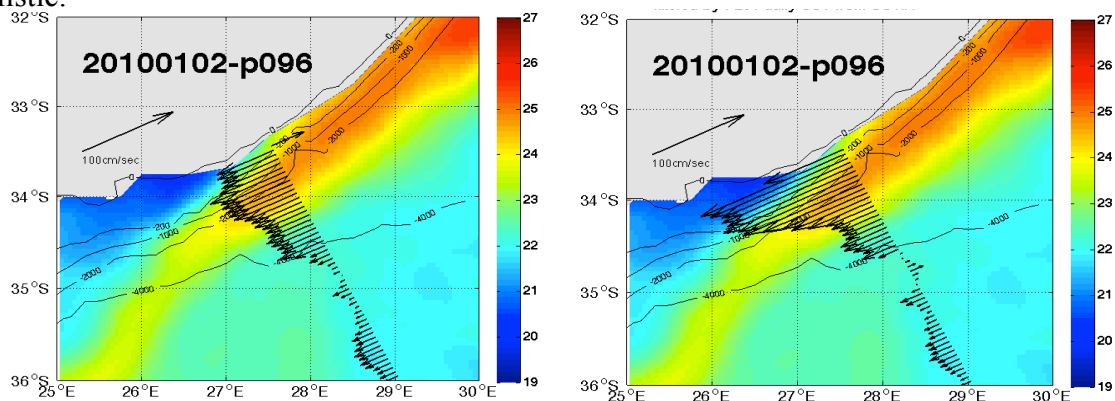

Figure 5. Absolute Current Velocities as derived from DTU10MDT (left) and MDT_CLS09 (right). Here and in the following plots: The contours represent the AC bathymetry from ETOPO2. Dates are indicated in yyyymmdd format.

3.3 Tracking of a meander downstream along Agulhas Current

In this section, a Natal Pulse (NP) that originated in the Natal Bight is followed as it moves downstream across five different Jason-2 altimetry tracks (Figure 6). The presence of a NP in the AC is clearly evident in the SST images marked by anomalously cold waters close to the coast. From the three NP events in 2010, the NP diameter is approximately 80 to 140 km expanding seaward as it moves downstream through the tracks. The time it takes to go from the first track to the last is between 40 and 80 days. According to the literature, diameter ranges from 30-200 km and the NP lasting between 50 and 150 days [*van Leeuwen et al.*, 2000]. Hence, the results of this analysis are in accordance to previous studies. NPs are characterized by low SSH, cold water, and northeastward velocities close to the continental shelf in satellite altimetry. The results presented here show that the portrayals of NP in SGVA of the coastal altimetry SLA data are in very good agreement with the SST.

3.4 Velocity anomaly structures in a non-meandering (top row) and meandering current (bottom row)

High-resolution data (ALES 20Hz) reach much closer to the coast, which shows that more data are retrieved. Yet an assessment of how good these data are is needed. All three datasets seem to capture the anomalies of the current and the passage of the meander, which results in high northeast velocity anomalies. However, the intensity of these velocities is represented differently in each of them, especially ALES. The use of the optimal filter in the last points near the coast need to be further tuned.

4. Conclusions

This study evaluates the ability of coastal reprocessed altimetry data to capture the current variability. Derived filtered velocities from the different datasets are able to capture the main characteristics of the AC and its mesoscale variability (i.e. meanders) but they experience differences, which have to be further understood and assessed. [*Powell and Leben*, 2004] filter seems to successfully remove HF noise although use of it near end points needs to be further explored especially in the higher resolution data. Careful consideration is needed in the use of MDT models. Tidal models are another source of uncertainty, in SLA hence velocities, to be taken into account. Derived filtered geostrophic altimetry velocities have been found in good agreement with SST images.
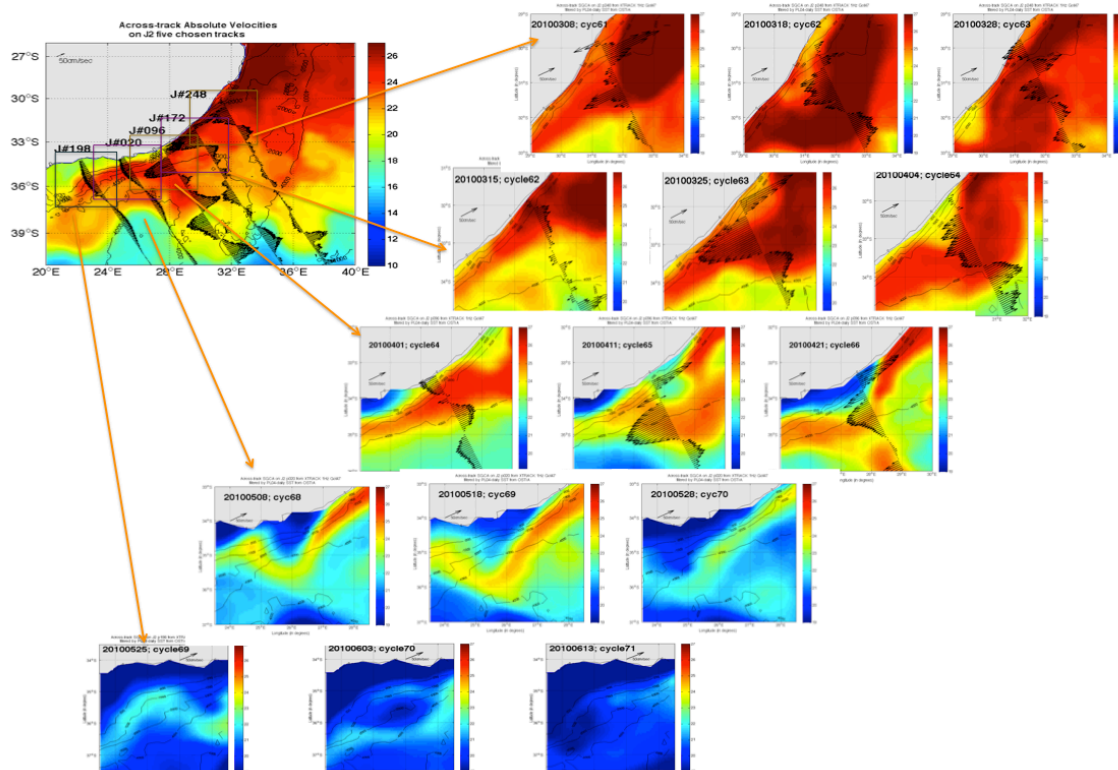
Figure 6. Translation of a Natal Pulse event along the Agulhas Current from March to June 2010 according to the thermal signature of the SST and surface geostrophic velocity anomalies (SGVA) from XTRACK 1Hz coastal altimetry SLA data. The analysis shown is on 5 different Jason2 altimetric tracks 248, 172, 096, 020, 198: starting north (first line of plots) to south (last line of plots) respectively. SGVA are missing from tracks 020 and 198. Colors show SST (°C) from GHRSST-OSTIA.
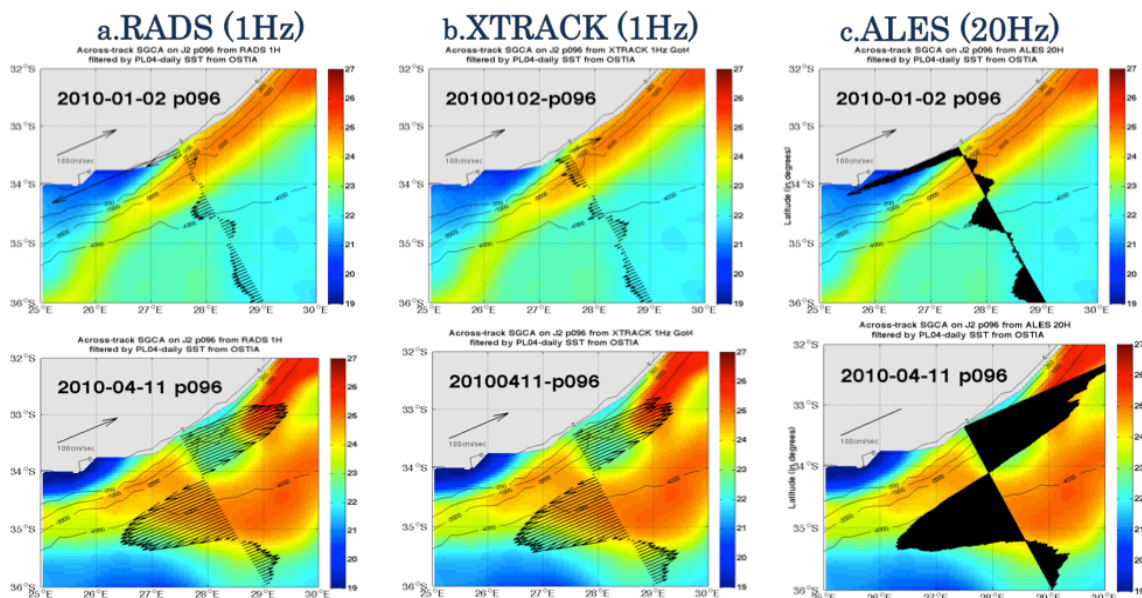

Figure 7. A stably flowing AC current as shown from SST (°C) GHRSST-OSTIA data (color in background) and the corresponding surface current velocity anomalies (top row) and a meandering current (bottom row) on Jason-2 track 096 from a) RADS, b) XTRACK and c) ALES.

References

Ansorge, and Lutjeharms (2005), Direct observations of eddy turbulence at a ridge in the Southern Ocean, *Geophysical Research Letters*, *32*(14), doi:10.1029/2005GL022588.

Beal (2009), A Time Series of Agulhas Undercurrent Transport, *Journal of Physical Oceanography*, *39*(10), 2436-2450, doi:10.1175/2009jpo4195.1.

Beal, and Bryden (1997), Observations of an Agulhas Undercurrent, *Deep-Sea Research Part I-Oceanographic Research Papers*, *44*(9-10), 1715-&.

Beal, De Ruijter, Biastoch, and Zahn (2011), On the role of the Agulhas system in ocean circulation and climate, *Nature*, *472*(7344), 429-436, doi:10.1038/nature09983.

Boebel, Rae, Garzoli, Lutjeharms, Richardson, Rossby, Schmid, and Zenk (1998), Float experiment studies interocean exchanges at the tip of Africa, *Eos Trans. AGU*, *79*(1), 7-8.

Boebel, Rossby, Lutjeharms, Zenk, and Barron (2003), Path and variability of the Agulhas Return Current, *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, *50*(1), 35-56, doi:Pii S0967-0645(02)00377-6.

Bryden, Beal, and Duncan (2005), Structure and transport of the Agulhas Current and its temporal variability, *Journal of Oceanography*, *61*(3), 479-492.

Cai (2006), Antarctic ozone depletion causes an intensification of the Southern Ocean super-gyre circulation, *Geophysical Research Letters*, *33*(L03712).

Casal, Beal, Lumpkin, and Johns (2009), Structure and downstream evolution of the Agulhas Current system during a quasi-synoptic survey in February–March 2003, *Journal of Geophysical Research*, *114*(C3), doi:10.1029/2008jc004954.

Dufau, Labroue, Peyridieu, Collard, Merlet, Cancet, Guillot, Picot, and Guinle (2012), The PISTACH products, altimeter data for coastal ocean, in *COSS-TT workshop*, edited, RSMAS, Miami.

Gordon (2003), Oceanography: The brawniest retroflection, *Nature*, *421*(6926), 904-905, doi:10.1038/421904a.

Lutjeharms (2006), *The Agulhas Current*, Springer.

Lutjeharms, and Ansorge (2001), The Agulhas Return Current, *Journal of Marine Systems*, *30*(1-2), 115-138.

Lutjeharms, and Bornman (2010), The Importance of the Greater Agulhas Current Is Increasingly Being Recognised, *South African Journal of Science*, *106*(3-4), 11-14, doi:Doi 10.4102/Sajs.V106i3/4.160.

Passaro, Marcello, Cipollini, Paolo, Vignudelli, Stefano, Quartly, Graham D. and Snaith, Helen M. (2014) ALES: A multi-mission adaptive subwaveform retracker for coastal and open ocean altimetry. Remote Sensing of Environment, 145, 173-189. (doi:10.1016/j.rse.2014.02.008).

Pearce (1977), Some Features of Upper 500 M of Agulhas Current, *Journal of Marine Research*, *35*(4), 731-753.

Pearce, and Grundlingh (1982), Is There a Seasonal-Variation in the Agulhas Current, *Journal of Marine Research*, *40*(1), 177-184.

Powell, and Leben (2004), An optimal filter for geostrophic mesoscale currents from along-track satellite altimetry, *Journal of Atmospheric and Oceanic Technology*, *21*(10), 1633-1642.

Roblou, Lamouroux, Bouffard, Lyard, Le Hénaff, Lombard, Marsaleix, De Mey, and Birol (2010), Post-processing altimeter data toward coastal applications and integration into coastal models., in *Coastal altimetry*, edited by Vignudelli S, Springer, Berlin, Germany.

Rouault, Penven, and Pohl (2009), Warming in the Agulhas Current system since the 1980's, *Geophysical Research Letters*, *36*, -, doi:Artn L12602
Doi 10.1029/2009gl037987.

Rouault, Pohl, and Penven (2010b), Coastal oceanic climate change and variability from 1982 to 2009 around South Africa, *African Journal of Marine Science*, *32*(2), 237-246, doi:10.2989/1814232x.2010.501563.

Van Leeuwen, De Ruijter, and Lutjeharms (2000), Natal pulses and the formation of Agulhas rings, *Journal of Geophysical Research-Oceans*, *105*(C3), 6425-6436.

Weijer, De Ruijter, Dijkstra, and Van Leeuwen (1999), Impact of interbasin exchange on the Atlantic overturning circulation, *J. Phys. Oceanogr.*, *29*, 2266–2284.

Weijer, De Ruijter, Sterl, and Drijfhout (2002), Response of the Atlantic overturning circulation to South Atlantic sources of buoyancy, *Global and Planetary Change*, *34*, 293-311.