ESTIMATING THE INDO-ATLANTIC SALT FLUX FROM ARGO AND ALTIMETRY

Graham D. Quartly[(1)], Josh Georgiou [(1)], Meric A. Srokosz[(1)]

[(1)] *National Oceanography Centre (NOC), Empress Dock, Southampton, Hants, UK: gdq / mas @noc.soton.ac.uk*

ABSTRACT

The interpretation of temperature and salinity profiles from ARGO floats is complicated by the fact that water mass properties are not simply slowly-varying over a region, but may have sharp fronts or eddies. By combining such profiles with contextual information gained from altimetry, we may measure temperature and salinity profiles separately for the background conditions and for features such as eddies within the region. A pilot study for the southeast Atlantic, through which large Agulhas rings (anticyclonic eddies) translate, indicated that the eddy characteristics only changed slowly, with the depth of the salinity minimum remaining at ~1100m, 250m deeper than in the environs, and that there was no noticeable effect on traversing the Walvis Ridge. Our initial estimate of the salt flux anomaly is 1.9×10^6 Kgs^{-1}, although a value almost 40% larger is obtained if a different eddy structure is assumed.

1. INTRODUCTION

Within the "Global Conveyor Belt", the system of currents linking all the Earth's oceans, the region to the south and west of South Africa is pivotal. In this region there is a net flow of surface warm salty water from the Indian Ocean into the southern Atlantic, but the majority of this so-called "Agulhas leakage" is in the form of eddies (rings) generated at the Agulhas Retroflection (see Fig. 1a) rather than through the mean currents. Although this exchange of heat and salt between the two oceans is known to be critical to the overall transport of the conveyor belt, it has been hard to quantify these heat and salt fluxes from limited hydrographic sections.

In this paper we combine the output from altimetry and ARGO floats to provide an estimate of the typical salt anomaly associated with an eddy. This is an initial look at the challenges of combining these two datasets, given that neither of them offers complete sampling of the eddies.

2. DATA SOURCES AND PROCESSING

This work makes use of salinity profiles from ARGO floats, using altimeter data to classify whether individual float profiles are inside an eddy or not.

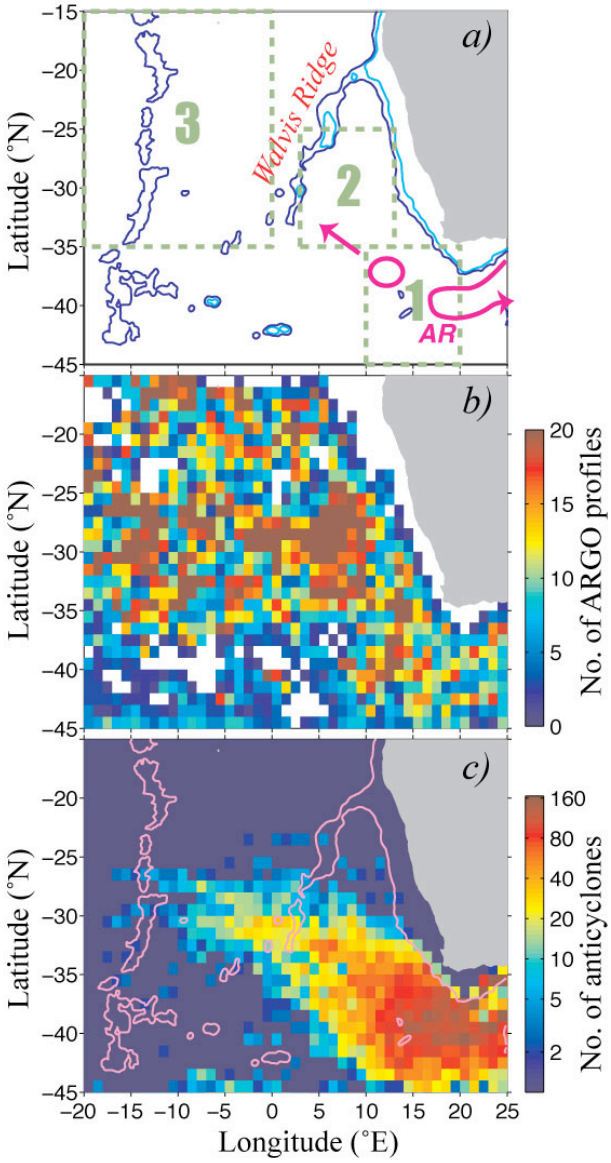

Figure 1. a) Bathymetry of study area, with schematic of flow regime (AR-Agulhas Retroflection). The dark blue isobaths indicate a depth of 3000m, whilst the lighter ones are for 2000m. The highlighted boxes are our chosen study regions. b) The occurrence of ARGO profiles totalled over 2000-2008 for each 1˚x1˚ box. c) Altimetric detection of anticyclone for each 1˚x1˚ box during 1993-2008. (Note, any eddy will be detected in many successive weekly fields.) Pink lines repeat the 3000m isobaths.

submitted to ESA Living Planet Symposium, Bergen, 28th Jun-2nd July 2010, ESA SP-686

2.1. ARGO floats

ARGO floats provide autonomous profiles of salinity and temperature every 10 days. Floats started being deployed in 2000, with the system design target of near 3000 floats in operation being achieved for 2007 onwards. The drifting depth of the floats is typically 1000 m, and thus mid-depth currents carry these instruments away from the main shipping routes used for deployment. However, even still, the convergence/divergence of currents and the barriers provided by shallow ridges mean that sampling is far from uniform (Fig. 1b), although much better than achieved solely by research ships.

Using the Coriolis website [1], we retrieved the "delayed mode" data, which have been quality-controlled. However, some ARGO profiles still contain suspect data, usually due to a malfunction of the conductivity sensor. Although an ARGO sensor with a constant bias may still be used to examine relative measurements (e.g. to locate the depth of the salinity minimum), we have here chosen to discard all profiles for which the deepest values were far from the expected range according to other databases. Applying these tests to both temperature and salinity data led to the rejection of ~35?% of profiles.

For subsequent analysis, we interpolate the profiles to intervals of 10m from 2000m to the surface, and for locating the depth of the salinity minimum, we fit a cubic polynomial to the salinity data between 200m and 1500m to overcome noise on the measurements.

2.2. Altimetry data

The source of altimetry data used here is the DUACS "Update" product available on a 0.25˚x0.25˚ grid [2]. This product combines all available altimeter data to yield a smooth estimate of sea surface height (SSH) every 7 days, using data from up to 6 days before and after the nominal date [3]. The r.m.s. variability in SSH at the Agulhas Retroflection is of order 40 cm (not shown), comparable with other large current systems such as the Gulf Stream and the Kuroshio.

The 7-day composite fields of SSH were converted into sea surface height anomalies (SSHA) by referencing to a long-term mean. As positive SSHA values may be due to anticyclonic eddies, changes in location of a permanent current or the seasonal cycle of heating (thermosteric increase in SSHA) we used the Okubo-Weiss parameter to identify area of rotation. This concept was pioneered by Isern-Fontanet et al. [4], who showed that this parameter, based on the double differential of SSHA, was able to distinguish between regions undergoing solid-body rotation and those where current shear dominates. Following Isern-Fontanet et al. [4] we adopted a threshold of $2 \times 10^{-11} s^{-2}$ for the detection of eddies. This criterion is then combined with a minimum SSHA of 10 cm (Fig. 2) to identify anticyclonic eddies. There are a large number of such identified features near the Agulhas Retroflection and along the route north-westward from there across the Walvis Ridge (Fig. 1c). [Cyclones are also common in the same area (not shown), but are not considered here, as they are likely to have spun off from the landward edge of the Agulhas Current (where there is strong current shear) and thus contain coastal waters of different origin to the Agulhas Current itself.

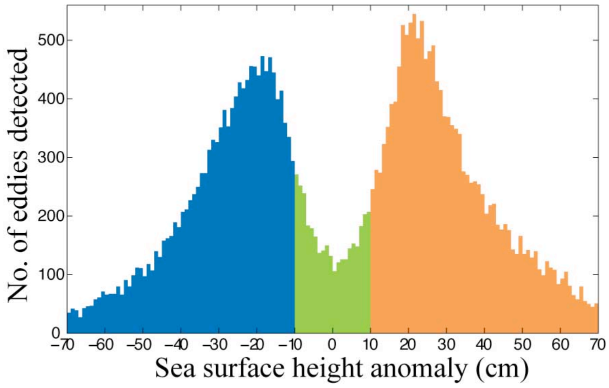

Figure 2. Histogram of sea surface height anomaly associated with detection of rotation features by Okubo-Weiss parameter. Analysis for region shown in Fig. 1, with separation into 1cm bins; 47.4% have a SSHA signature ≥ 10cm, with 42.4% ≤ -10cm.

3. STUDY REGIONS AND EXPECTED EFFECT OF BATHYMETRY

The intention of this project was to monitor the changes in properties of Agulhas eddies as they migrate northwestwards. There have only been a few cases where repeated hydrographic surveys have been achieved of an individual Agulhas eddy, and the water mass properties were found to only change slowly over a few months [5]. As ARGO floats are not directed, their sampling of the eddy field is somewhat random, with occasional consecutive 10-day profiles from within a particular propagating feature. However, in general the ARGO sampling does not permit long-term monitoring of any individual eddy. Instead we identify three regions (highlighted in Fig. 1a) and, for each, construct a mean from those ARGO profiles within eddies. As background T-S (temperature-salinity) quantities change throughout the whole region, we also constructed mean profiles for each box from all ARGO profiles outside eddies.

The three boxes represent different stages on an eddy's route from its genesis at the Agulhas Retroflection into the S. Atlantic, with the third box being four times the area of the others, since clearly identified eddies are much rarer further west (Fig. 1c). Regions 2 and 3 lie either side of the Walvis Ridge, which rises to within 2000m of the surface. This, then, acts as a significant barrier to the propagation of eddies, with preferred routes being identified through gaps in the topography. Using a two-layer model, Kamenkovich et al [6] showed that the Walvis Ridge should have a significant effect on the structure of eddies, with those that manage to cross the ridge becoming more baroclinic than those that do not. Such changes to an eddy's currents, and T-S properties should be detectable by ARGO floats.

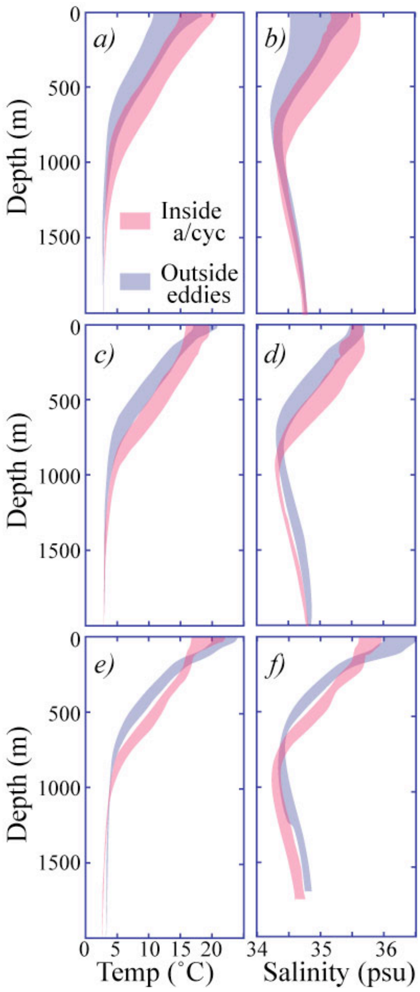

Figure 3. Range of temperature and salinity profiles found within the 3 sites, separated as to whether inside an anticyclone or not. Curves represent mean ± 1std. dev. a,b) Site 1 at Agulhas Rretroflection, c,d) Site 2 east of Walvis Ridge, e,f) Site 3 west of Walvis Ridge.

4. MEAN ARGO PROFILES

For selected region 1 there are a large number of ARGO profiles, both within anticyclones and outside any eddies. Fig. 3a,b shows the range of T and S profiles for that region. There is a considerable spread in values in the top 1000m, especially for the profiles at site 1. Partially this will be because even the Okubo-Weiss criterion has difficulty in clearly locating eddies in a region of complex currents. A second aspect is that the background conditions span a range of water masses, from those either side of the southern subtropical front [X]. The salinity profiles show a minimum of around 34.3 psu at mid-depth. For profiles outside eddies the depth of the salinity minimum is 800m, with a standard deviation of ~150m (see Tab. 1), whilst within anticyclones it is considerably depressed to 1050m. A part of the apparent variability in depth is due to the difficulty of unambiguously defining eddies in this region of complex currents and high mesoscale variability. However, when standard errors are computed (which are <30m), it is clear that the differences in depth of the salinity minimum are significant.

Table 1 Depth in metres of salinity minimum (with std. dev. of values given in parentheses.)

Location	Inside eddy	Outside eddy
Site 1	1050 ± 200	800 ± 150
Site 2	1100 ± 125	850 ± 125
Site 3	1100 ± 75	850 ± 175

The selected ARGO profiles for boxes 2 and 3 (Figs. 3c-f) show less variation than for box 1, but do replicate the findings for box 1 concerning the depth of the salinity minimum (Tab. 1). Investigation of the 4˚C isotherm (not shown) similarly points to a marked depression of water layers within the eddies across all three regions. For sites 2 and 3 there are only roughly a dozen ARGO profiles in each that are unequivocally inside eddies, whereas there are hundreds contributing to our estimate of the background conditions.

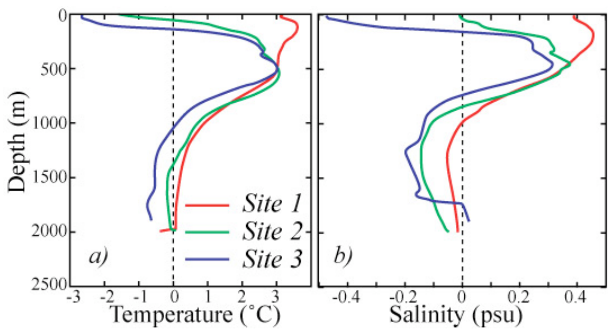

Figure 4. Temperature and salinity anomalies (eddy minus background) associated with anticyclones at each of the 3 sites.

Fig. 4 emphasises the differences in water properties between inside and outside these anticyclones. The most striking feature is the maximum difference in temperature and salinity at around 300-650m; it shows that Agulhas eddies are warmer by ~4˚C and saltier by around 0.5psu. Progressing from site 1 to site 2 to site 3 shows a gradual reduction in the anomalies near the surface. A major part of this is due to the change in background conditions as the eddies move north-westward away from the retroflection into a region where surface waters are warmer and saltier. However, some of the change is due to the strong air-sea interaction eroding the surface temperature signature [8] and the enhanced buoyancy flux increasing the density and thus potentially mixing the changes down over the top 300m [8].

5. QUANTIFYING FLUXES

In this section we make a simple estimate of the salt anomaly content of an Agulhas eddy. For the eddy generation region (site 1), the salinity profiles inside and outside the eddy converge below 1000m. This was also an eddy depth determined by McDonagh et al [9] using the 3.5˚C isotherm. We consider the eddies to have a typical radius at the surface of 150 km [10] and assume that this decreases linearly to zero at 1000m. The total salt anomaly is then determined by integrating the volume of each 10 m thick disc (Fig. 5a) multiplied by the observed salinity difference (Fig. 5b). We derive the total salinity anomaly to be 9.8×10^{12} Kg, which assuming six eddies per year [11] amounts to a flux of 1.9×10^{6} Kgs^{-1}. Integration using a hemispherical model for the eddy (rather than conical) gives values ~40% larger; thus the overall uncertainty on this estimate is large, until we have a clearer constraint on the correct eddy structure to use.

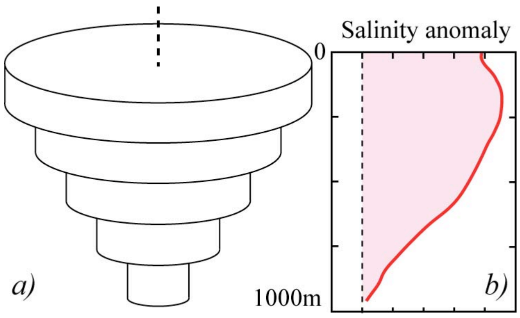

Figure 5. Integration of salt flux anomaly. a) Schematic of conical representation (series of 10m thick discs). b) Salinity anomaly at site 1.

6. SUMMARY AND DISCUSSION

For some years now ARGO floats have been used to contribute data towards the construction of mean T and S properties in parts of the sea with few dedicated oceanographic cruises. In this paper we have demonstrated that the added synoptic view from altimetry may be used to enable ARGO profiles to be categorised as within eddies or representing the background conditions. This development work was carried out for eddies generated at the Agulhas Retroflection, where features are known to be large and coherent (and thus relatively easily detected by altimetry) and have large temperature and salinity anomalies. Although the variability in each classification (inside/outside) was large, sufficient profiles were recovered to place robust bounds on the mean. This confirmed that, at site 1, Agulhas eddies have, over the top 1000m, waters that are typically 4˚C warmer and 0.4 psu saltier than their environs, and that the salinity minimum is depressed from 800m to 1050m.

For sites 2 and 3, the salinity minimum within the eddy is still at 1100m, but the temperature and salinity differences with respect to the environs have changed, partially through moving into warmer saltier waters towards the Equator, and partially through surface heat loss being mixed down within the eddy [8]. Contrary to the theoretical expectation of Kamenkovich et al. [6], crossing the Walvis Ridge does not seem to generate any pronounced change in vertical structure between sites 2 and 3.

We estimate that eddies transport a salt flux anomaly of 1.9×10^{6} Kgs^{-1} between the Indian and Atlantic Oceans. At present, our error bars are large, since the integral depends upon the depth and size of the feature, as well as its geometrical shape. Our estimate is consistent with that of van Ballegooyen [12] of 2.5×10^{6} Kgs^{-1}, again assuming 6 eddies per year.

7. ACKNOWLEDGEMENTS

These data were collected and made freely available by the International Argo Project. Gridded altimetry data were provided by CLS/Aviso. The initial work for this paper was done as part of a MSc research project at the School of Ocean and Earth Sciences, University of Southampton.

8. REFERENCES

[1] http://www.coriolis.eu.org/cdc/dataSelection/cdcdataSelections.asp

[2] http://www.aviso.oceanobs.com/en/data/product-information/duacs/

[3] LeTraon P.Y., P. Gaspar, F. Bouyssel, and H. Makhmara, Using Topex Poseidon data to enhance ERS-1 data., *J. Atmos. Oceanic Tech.* 12, 161-170, 1995.

[4] Isern-Fontanet, E. Garcia-Ladona, and J. Font, Identification of marine eddies from altimetric maps, *J. Atmos. Oceanic Tech.* 20, 772-778, 2003.

[5] van Aken HM, van Veldhoven AK, Veth C, de Ruijter WPM, van Leeuwen PJ, Drijfhout SS, Whittle CP, Rouault M, Observations of a young

Agulhas ring, Astrid, during MARE in March 2000 *Deep-Sea Res, II*, 50, 167-195, 2003.
[6] Kamenkovich, V. M., Y.P. Leonov, D.A. Nechaev, D.A. Byrne, and A.L. Gordon, On the influence of bottom topography on the Agulhas eddy, *J. Phys. Oceanogr.*, 26, 892-917, 1996.
[7] Belkin, I.M., and A.R. Gordon, Southern Ocean fronts from the Greenwich meridian to Tasmania, *J. Geophys. Res.*, 101, 3675-3696, 1996.
[8] Olson, D.B.R., R. Fine, and A.L. Gordon, Convective modification of water masses in the Agulhas, *Deep-Sea Res.*, 39, 163-181, 1992.
[9] McDonagh, E.L., K.J. Heywood, and M.P. Meredith, On the structure, paths and fluxes associated with Agulhas rings, *J. Geophys. Res.*, 104, 21007-21020, 1999.
[10] Lutjeharms, J.R.E. and R.C. van Ballegooyen, The retroflection of the Agulhas Current. *J. Phys. Oceanogr.*, 18, 1570–1583, 1988.
[11] Gordon, A., Indian-Atlantic transfer of thermocline water at the Agulhas retroflection, *Science*, 223, 1030-1034, 1985.
[12] van Ballegooyen, R.C., M.L. Grfindlingh, and J.R.E. Lutjeharms, Eddy fluxes of heat and salt from the southwest Indian ocean into the southeast Atlantic ocean: a case study, *J. Geophys. Res.*, 99, 14053-14070, 1994.