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Rémi Laxenaire, Sabrina Speich, Alexandre Stegner. Evolution of the thermohaline structure of one Agulhas Ring reconstructed from satellite altimetry and Argo 2 floats. 2019. hal-02340055v1

HAL Id: hal-02340055 https://hal.science/hal-02340055v1

Preprint submitted on 30 Oct 2019 (v1), last revised 13 Dec 2023 (v2)

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Evolution of the thermohaline structure of one Agulhas Ring reconstructed from satellite altimetry and Argo floats

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7 Key Points:

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- $_{\mbox{\tiny 8}}$ $\,$ $\,$ $\,$ Lagrangian reconstruction of an Agulhas Ring sampled by an Argo float for more
- ⁹ than 1.5 years
- ¹⁰ In situ evidence of the subduction of an Agulhas Ring
- The reconstructed Agulhas Ring is characterized by two mode water cores

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12 Abstract

The transfer of Indian Ocean thermocline and intermediate waters into the South At-13 lantic via the Agulhas leakage is generally believed to be primarily accomplished through 14 mesoscale eddy processes, essentially anticyclones known as Agulhas Rings. Here we take 15 advantage of a recent eddy tracking algorithm and Argo float profiles to study the evo-16 lution and the thermohaline structure of one of these eddies over the course of 1.5 years 17 (May 2013-November 2014). We found that during this period the ring evolved accord-18 ing to two different phases: During the first one, taking place in winter, the mixing layer 19 in the eddy deepened significantly. During the second phase, the eddy subsided below 20 the upper warmer layer of the South Atlantic subtropical gyre while propagating west. 21 The separation of this eddy from the sea surface could explain the decrease in its sur-22 face signature in satellite altimetry maps, suggesting that such changes are not due to 23 eddy dissipation processes. It is a very large eddy $(7.1 \times 10^{13} \text{ m}^3 \text{ in volume})$, extending, 24 after subduction, from a depth of 200-1200 m and characterized by two mode water cores. 25 The two mode water cores represent the largest eddy heat and salt anomalies when com-26 pared with the surrounding. In terms of its impact over one year, the north-westward 27 propagation of this long-lived anticyclone induces a transport of 2.2 Sv of water, 0.008 28 PW of heat, and 2.2×10^5 kg s⁻¹ of salt. These results confirm that Agulhas Rings play 29 a very important role in the Indo-Atlantic interocean exchange of heat and salt. 30

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1 Plain Language Summary

The transfer of the Indian Ocean waters to the South Atlantic Ocean is generally 32 believed to be primarily accomplished through anticyclonic eddies known as Agulhas Rings. 33 There have been various studies investigating these eddies from sparse in-situ and satel-34 lite observations. Here we take the advantage of the complementary information provided 35 by eddies detected from satellite maps and free-drifting profiling floats measuring the up-36 per 2000 m of the ocean, to reconstruct the internal structure of one of them. This re-37 construction shows that this Agulhas Ring quits the surface layer and slowly sinks into 38 the subsurface as it drifts westward into the Atlantic Ocean. The ring is a very large eddy 39 extending down to 1200 m of depth and characterized by two cores showing tempera-40 ture anomalies up to 4°C when compared with the surrounding South Atlantic waters. 41 These results confirm that Agulhas Rings play a very important role in the Indo-Atlantic 42 interocean exchange of heat and salt. 43

44 2 Introduction

Mesoscale eddies are ubiquitous in the World Ocean (Chelton et al., 2007, 2011).
Their energy generally exceeds that of the mean flow by an order of magnitude or more
(Stammer, 1997; Wunsch, 1999) and they are thought to have a major impact on the spreading of hydrological properties by advecting them for considerable distances and over long
periods. In particular, their influence is seen as key in the transfer of heat, salt, mass,
and biogeochemical properties across the World Ocean (McWilliams, 1985).

Over the last 25 years, satellite altimetry has provided a regular, global, high-resolution monitoring of sea level and ocean circulation variations (Morrow & Le Traon, 2012). These data constitute a precious time series with regular spatial sampling capable of recovering around 60% of the variability in the 65 to 300 km mesoscale band (Pujol et al., 2016). For this reason, they allow us to quantitatively investigate the upper ocean dynamics, and they have been shown to be particularly well suited to the study of mesoscale eddies (e.g., Chelton et al., 2011).

Since the early period of satellite altimetry, because of the large extent and intense 58 altimetry signal of Agulhas Rings, various studies have focused on these Rings and their 59 spatio-temporal evolution (e.g., Byrne et al., 1995; Gründlingh, 1995; Schouten et al., 60 2000; Dencausse et al., 2010; Beron-Vera et al., 2013; Froyland et al., 2015; Wang et al., 61 2015, 2016; Guerra et al., 2018; Nencioli et al., 2018). Agulhas Rings are mesoscale an-62 ticyclones spawned south of Africa by the South Indian western boundary current, the 63 Agulhas, at its Retroflection. They are large (100 to 400 km diameter) rings of Agul-64 has Water that enter the Cape Basin southwest of Africa, before moving westward across 65 the South Atlantic Ocean (e.g., Byrne et al., 1995; Schouten et al., 2000; Biastoch et al., 66 2009; Guerra et al., 2018; Laxenaire et al., 2018). The evolution and fate of Agulhas Rings 67 are important aspects, since these rings are thought to account for an significant per-68 centage of Indian water leakage into the Atlantic (e.g., Gordon & Haxby, 1990; Goni et 69 al., 1997; A. Doglioli et al., 2006). This leakage impacts the Atlantic Meridional Over-70 turning Circulation (AMOC) and the related meridional transport of heat, freshwater, 71 and biogeochemical properties, by influencing its strength (Weijer et al., 1999, 2002; van 72 Sebille & van Leeuwen, 2007), stability (Weijer et al., 2001) and variability (Biastoch et 73 al., 2008; Biastoch & Böning, 2013). Satellite data give access to the evolution of the sur-74 face properties of these eddies (e.g., Byrne et al., 1995; Schouten et al., 2000; Lehahn et 75

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al., 2011; J. Souza et al., 2014; Froyland et al., 2015; Guerra et al., 2018; Laxenaire et 76 al., 2018). In particular, the above-mentioned studies show that the surface signature 77 of Agulhas Rings decreases dramatically west of the Agulhas Retroflection and across 78 the southern Cape Basin, and continues to decrease gradually across the South Atlantic 79 Ocean (e.g., Froyland et al., 2015; Guerra et al., 2018; Laxenaire et al., 2018). However, 80 the majority of the previous studies based on satellite altimetry and with the aim of re-81 covering the complete trajectories of one or more Agulhas Rings were not able to track 82 all of them back from their area of Retroflection documenting their first detection in the 83 vicinity of the Cape Basin (e.g., Byrne et al., 1995; Lehahn et al., 2011; J. Souza et al., 84 2014; Guerra et al., 2018). 85

This is most likely due to the non-consideration by previous studies of the com-86 plex nature of Agulhas Ring trajectories that undergo many eddy splitting and merg-87 ing events (Schouten et al., 2000; Dencausse et al., 2010; Kersalé et al., 2018; Laxenaire 88 et al., 2018). For example, studying Agulhas Rings in the Cape Basin, Dencausse et al. 89 (2010) showed that the number of these eddies entering the Basin is multiplied by a fac-90 tor of two when considering eddy splittings. Moreover, when focusing on the evolution 91 and dissipation of three specific Agulhas Rings, Nencioli et al. (2018) observed a merg-92 ing of two of them in the vicinity of the South Atlantic Ocean. Consequently, these in-93 teractions, impacting the pattern of the eddy evolution and dissipation, are important 94 if we are to understand the mechanisms of ocean circulation and how Agulhas Rings in-95 fluence the Earth's climate. Indeed, in the published literature it has been documented 96 how Agulhas Ring surface properties change and how their disappearance from satellite 97 altimetry maps is often associated with eddy dissipation processes, albeit direct obser-98 vations of the latter are lacking. On the other hand, when these eddies are tracked over 99 longer distances and for longer periods, and explicitly taking into account eddy merg-100 ings and splittings (Laxenaire et al., 2018), intense variations of their surface properties 101 appear to be intimately correlated with such events. 102

Another limitation of satellite observations is that they do not provide information about the eddy vertical structure and how this evolves en route. Agulhas Rings have only been sampled occasionally by *in situ* observations from ships in the Cape Basin (e.g., Gordon et al., 1987; Duncombe Rae et al., 1992; van Ballegooyen et al., 1994; Duncombe Rae et al., 1996; Arhan et al., 1999; Garzoli et al., 1999; McDonagh et al., 1999; Schmid et al., 2003; Gladyshev et al., 2008; Arhan et al., 2011; Casanova-Masjoan et al., 2017), in

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the Southeast Atlantic (M. S. McCartney & Woodgate-Jones, 1991; Arhan et al., 1999), 109 or from Argo profiling floats (J. M. A. C. Souza et al., 2011; Nencioli et al., 2018). How-110 ever, with the exception of the observations reported in Nencioli et al. (2018), J. M. A. C. Souza 111 et al. (2011) and Arhan et al. (1999), Agulhas Rings have not been sampled by in situ 112 observations farther west of the Southeast Atlantic, nor has it been possible to evalu-113 ate accurately their internal evolution from the Agulhas Retroflection onward. Concern-114 ing this last point, Schmid et al. (2003) and Nencioli et al. (2018) reported on the en-115 route evolution of Agulhas Rings. Schmid et al. (2003) discussed an Agulhas Ring sam-116 117 pled twice, at six-month intervals, in the southern Cape Basin which showed an intense change of the upper-layer eddy properties (essentially in terms of temperature and den-118 sity, very likely due to strong seasonal air-sea interactions) and a freshening of interme-119 diate waters. Nencioli et al. (2018) also considered the intense variation of properties in 120 the upper 200 m of an Agulhas Ring crossing the South Atlantic and discussed the mod-121 ifications in the internal structure of this eddy. Moreover, the internal structure of this 122 eddy was characterized by a subsurface core of homogeneous water that the authors iden-123 tified as Mode Waters (MWs), in line with previous observations of subsurface intensi-124 fied structures discussed by Arhan et al. (1999). 125

MWs are thick layers of homogeneous subsurface waters whose existence is thought 126 to depend, as a precondition, on the formation of deep mixed layers (e.g., Hanawa & Tal-127 ley, 2001). MWs have been identified in every ocean basin, always on the warm side of 128 a current or front (e.g., M. McCartney, 1977; M. S. McCartney, 1982; Hanawa & Tal-129 ley, 2001). They are generally distributed below the surface far beyond their formation 130 areas. Among these are Western Subtropical Mode Waters (WSTMW) usually associ-131 ated with subtropical gyres, and Subantarctic Mode Waters (SAMW) associated with 132 the subpolar fronts on the poleward boundaries of the southern hemisphere subtropical 133 gyres (e.g., M. McCartney, 1977; Hanawa & Talley, 2001). MWs are correlated with large 134 surface heat loss from the ocean and their low potential vorticity arises as a result of con-135 vection (e.g., Hanawa & Talley, 2001). Various MWs in the South Atlantic are discussed 136 in the literature. Of these, Provost et al. (1999) documented from repeated hydrographic 137 cruises two types of MW: the South Atlantic Subtropical Mode Water (SASTMW) found 138 in the western subtropical gyre and the South Atlantic Eastern Subtropical Mode Wa-139 ter (SAESTMW) observed at the eastern edge of the subtropical gyre. Sato and Polito 140 (2014) introduced a new definition of SASTMW by analyzing Argo float data. Using a 141

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clustering method they found three different varieties of SASTMW that differed in their 142 hydrological properties and geographical location. These do not correspond completely 143 with Provost et al. (1999)'s SASTMWs definition as they are defined from many more 144 vertical profiles and over a larger area of the South Atlantic. It should be noted here that, 145 using the eddy database from Chelton et al. (2011), Sato and Polito (2014) checked whether 146 SASTMWs were correlated with the presence of mesoscale eddies. They did not find a 147 high correspondence. However, when these authors did observe a correspondence between 148 SASTMW and eddies, they found that 75% of them were anticyclones. 149

Very recently, de Souza et al. (2018) described the origin of South Atlantic MWs 150 by decomposing thermocline waters as a product of the mixing of different MW varieties. 151 They identified, among others, a particular SASTMW that is located along the Agul-152 has Rings main route where they are an important contributor of thermocline water. In 153 addition, de Souza et al. (2018) identified a westward deepening of SASTMW where this 154 mixes with MWs originating from the Indian Ocean. They attributed such a deepening 155 to a sinking of the core of Agulhas Rings during their crossing of the South Atlantic. This 156 echoes citetHerbette:2004 who numerically demonstrated that Agulhas Rings could subduct 157 below a front. Taking into account these works we might ask whether Agulhas Rings might 158 be an active process of MW formation as speculated by de Souza et al. (2018), and whether 159 the variations of surface properties observed in the altimetry maps are linked with lat-160 eral mixing of waters between the eddy core and the environment, or result from a dif-161 ferent process acting on the internal properties of eddies. Finally, by using *in situ* data, 162 numerous authors (Gordon et al., 1987; M. S. McCartney & Woodgate-Jones, 1991; Dun-163 combe Rae et al., 1992; van Ballegooyen et al., 1994; Duncombe Rae et al., 1996; Arhan 164 et al., 1999; Garzoli et al., 1999; McDonagh et al., 1999; Schmid et al., 2003; Gladyshev 165 et al., 2008; Arhan et al., 2011; Casanova-Masjoan et al., 2017) have provided various 166 estimates of Agulhas Ring volume, heat, and salt transports. It would be interesting to 167 examine how this series of observed Agulhas Rings compare with each other and whether 168 any general information about Agulhas Rings distribution can be derived. 169

In order to provide an additional step forward in the assessment of Agulhas Ring dynamics and changes across the Atlantic, we discuss here the evolution of one of these eddies in the South Atlantic, sampled by a high number of vertical profiles over more than a year. By making sure that the Argo profiles we used were meaningful observations of the eddy core, we isolated a period of the eddy lifetime during which the eddy

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subducted below the upper-ocean layer and where thermohaline properties remained steady.
During such a period of time, the eddy structure might be considered sufficiently stationary to permit a meaningful reconstruction. By undertaking a comprehensive comparison with Agulhas Ring properties discussed in the literature, we proved the robustness of our results and highlighted the role of specific MWs responsible for important
heat and salt content anomalies with regard to the surrounding waters.

The paper is organized as follows. In Section 2, the data we have used are described and the methods we have developed are presented. In Section 3, the evolution of the surface and vertical eddy characteristics derived from satellite altimetry and Argo profiles is presented, as well as the reconstruction of the Agulhas Ring's mean internal structure in the South Atlantic. Section 4 discusses the results we obtained in the context of previous studies and assessments. A summary of the study and our conclusions about the results are provided in Section 5.

¹⁸⁸ 3 Data and Methods

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3.1 The South Atlantic Eddy Atlas

We selected Agulhas Rings from the South Atlantic eddies we identified and tracked 190 them in time with the Tracked Ocean Eddies (TOEddies) automatic detection algorithm 191 (Laxenaire et al., 2018) applied over more than 24 years (01/1993 to 05/2017) of the "all-192 sat-merged" series (Duacs/AVISO+, 2015) of delayed time daily satellite altimetry maps 193 gridded at $1/4^{\circ}$ in the South Atlantic and Southeast Indian oceans [70°W-65°E; 55°S-194 15° S] ((Laxenaire et al., 2018), see Figure 1a). The TOEddies method is based on the 195 algorithm proposed and developed by Chaigneau et al. (2008, 2009) and Pegliasco et al. 196 (2015). The eddy detection algorithm is a two-step process: it identifies the occurrences 197 of eddies before deriving their trajectories. 198

The key assumption of eddy detection by the TOEddies algorithm is that mesoscale eddies satisfy the geostrophic balance. Therefore, the instantaneous eddy streamlines should coincide with the closed isolines of the daily Absolute Dynamic Topography (ADT) maps. First, TOEddies identifies the local extrema (maxima and minima) of ADT by comparing each ADT grid point to its eight neighbors as possible eddy centers in the same way that other methods defined extrema from Sea Level Anomaly (SLA) maps (e.g., Chelton et al., 2011; Faghmous et al., 2015). Next, it looks for the outermost closed ADT

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Figure 1. The study domain presented in terms of a) the local bathymetry from the ETOPO2 dataset (Smith & Sandwell, 1997) and b) the percentage of time each $2^{\circ} \times 2^{\circ}$ grid cell is occupied by the core of an eddy occurrence as part of the Agulhas Ring Eddy Network (Laxenaire et al., 2018). Figure modified from Laxenaire et al. (2018).

contour around each extremum. The module of the ADT difference between the extremum 206 and this contour defines the amplitude of the detected eddy, which is considered a proxy 207 of the eddy (surface) intensity. To filter out weak extrema we require that the extremum 208 amplitude is greater than a threshold of 1×10^{-3} m. This value, which is small in com-209 parison to the precision of satellite altimetry maps, was obtained by Laxenaire et al. (2018) 210 to improve the coherence between the TOEddies Atlas and eddies identified from sur-211 face drifting buoys by Lumpkin (2016). The requirement to take into account eddies as-212 sociated with amplitudes smaller than 1×10^{-2} m was demonstrated by Faghmous et al. 213 (2015).214

In addition to the outer closed ADT contour, TOEddies also identifies the contour 215 where the azimuthal velocity of the eddy is at its maximum. This contour, associated 216 with the gradient of the ADT, is expected to be less dependent on the hydrological struc-217 tures out of the eddies and easier to compare with in situ data. TOEddies uses for this 218 purpose the geostrophic velocity derived from ADT maps and computes along each closed 219 contour the mean azimuthal velocity $\langle V \rangle$. The contour, corresponding to V_{max} = 220 $max(\langle V \rangle)$, is called the characteristic eddy contour. The area of the eddy within 221 this contour defines what we designate as the eddy core. The mean radius, R_{Vmax} , of 222 this eddy-core area, A_{Vmax} , is derived according to the following equation: 223

$$R_{Vmax} = \sqrt{\frac{A_{Vmax}}{\pi}} \tag{1}$$

We call this the speed radius because it is associated with V_{max} . In the same way, 224 TOEddies defines the maximum radial extent R_{out} associated with the outer closed con-225 tour of the eddy. This limit is important as the eddy core defined by R_{Vmax} cannot be 226 used alone to define either the area of influence of the eddy or the surface limiting the 227 portion of the eddy where waters are trapped within the structure. This can be better 228 understood by considering the ratio between the eddy azimuthal and drift speeds. This 229 ratio is a nonlinear parameter delimiting the area of water trapped in a coherent struc-230 ture (Flierl, 1981; Chelton et al., 2011). For example, Agulhas Rings are characterized 231 by a drifting speed of about $5-8 \times 10^{-2}$ m s⁻¹ (e.g., Casanova-Masjoan et al., 2017; Nen-232 cioli et al., 2018; Guerra et al., 2018) whereas V_{max} is of the order of several 10^{-1} m 233 s^{-1} (e.g., Casanova-Masjoan et al., 2017). This suggests that water outside of the limit 234 of R_{Vmax} can be trapped within these eddies. This is confirmed by J. M. A. C. Souza 235

et al. (2011) who identified, in the South Atlantic, a horizontal extension of the eddy-236 trapped waters region larger than 150 km, whereas the typical R_{Vmax} of Agulhas Rings 237 is, in this area, 60-80 km (Guerra et al., 2018; Nencioli et al., 2018; Laxenaire et al., 2018). 238 At this stage of the TOEddies algorithm sequences, the eddy center corresponds 239 to the local extremum of ADT, which corresponds to a defined AVISO map grid point 240 that might not coincide with the position of the eddy center. To avoid such a constraint, 241 TOEddies computes the centroid of the eddy-core area to determine the geometrical cen-242 ter of the eddy. Finally, the TOEddies algorithm computes the vortex Rossby number 243 (Ro) that we use to quantify the (surface) eddy intensity (e.g., Chelton et al., 2011; Mkhinini 244 et al., 2014; Le Vu et al., 2018; Laxenaire et al., 2018). Ro is given by the following equa-245 tion: 246

$$Ro = \frac{V_{max}}{f \times R_{Vmax}} \tag{2}$$

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where f is the Coriolis parameter.

In order to follow the position of each detected structure, TOEddies uses an algo-248 rithm based on the overlapping of eddy contours at consecutive time steps (Pegliasco et 249 al., 2015; Laxenaire et al., 2018). Using the daily AVISO fields, the method relies on the 250 fact that mesoscale eddies move slowly (displacements of less than 10 km/day (e.g., Gar-251 zoli et al., 1999; Chelton et al., 2011; Laxenaire et al., 2018)) relative to their typical radii 252 which span the range 20-200 km (Carton, 2001). Consequently, the areas occupied by 253 an eddy for two consecutive days overlap, and this can be used to track eddies (Pegliasco 254 et al., 2015). Laxenaire et al. (2018) determined that the optimal percentage of the eddy 255 area overlapping between two consecutive days was equal to or larger than 50% of the 256 smallest area among the two eddies. This parameter reduces the number of spurious iden-257 tifications (Laxenaire et al., 2018). If no eddy satisfies the condition of area overlapping 258 for consecutive time steps, the research is extended for up to 5 consecutive days (i.e. half 259 of the 10 days used by Le Vu et al. (2018)), leaving the overlapping parameter unchanged. 260

The main advantage of the TOEddies tracking method is that it also allows for taking into account the merging of eddies, that is, when two or more eddies coalesce together to form one eddy, as well as the splitting of one eddy into two or more smaller eddies. Laxenaire et al. (2018) and Le Vu et al. (2018) have shown that merging and splitting

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events strongly impact the reconstruction of eddy trajectories and lifetimes. When these 265 events occur, the segments of trajectories are reconstructed by associating pairwise ed-266 dies. In the case of a splitting, a cost function (CF), modified from Pegliasco et al. (2015) 267 and Le Vu et al. (2018) and presented in equation 3, is applied to the eddy parent and 268 the two or more eddy descendants. The CF compares changes (Δ) in the position of the 269 eddy center (Center), Rossby number (Ro), and radius of maximum speed (R_{Vmax}) of 270 the eddies where $\overline{\Delta \alpha}$ and $\sigma_{\Delta \alpha}$ denote, respectively, the mean and the standard devia-271 tion of the differences of a variable computed from all the association of eddies either dur-272 ing a splitting or a merging event. The two trajectory segments that minimize CF are 273 identified as the main trajectories whereas the remaining segments are identified as the 274 product of the splitting and referred to higher order trajectories (Laxenaire et al., 2018). 275 Similarly, main trajectories are identified in the case of a merging. 276

$$CF = \sqrt{\left(\frac{\Delta \text{Center} - \overline{\Delta \text{Center}}}{\sigma_{\Delta} \text{Center}}\right)^2 + \left(\frac{\Delta \text{Ro} - \overline{\Delta \text{Ro}}}{\sigma_{\Delta} \text{Ro}}\right)^2 + \left(\frac{\Delta \text{R}_{\text{Vmax}} - \overline{\Delta} \text{R}_{\text{Vmax}}}{\sigma_{\Delta} \text{R}_{\text{Vmax}}}\right)^2} \quad (3)$$

In this study, we consider trajectories whose lifetime is equal to or longer than one month (i.e. 4 weeks) to reduce the size of the database. This selection is reasonable in the case of Agulhas Rings that have, on average, a lifespan of a few months to several years (e.g., Byrne et al., 1995).

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3.2 Sea Surface Temperature

It was shown by Lehahn et al. (2011) and J. Souza et al. (2014) that Agulhas Rings 282 crossing the Atlantic Ocean can be associated with specific surface properties. In this 283 framework, we will use Sea Surface Temperature (SST) data to characterize the eddies. 284 For this purpose we retrieved the level 4 ODYSSEA SST daily database (Dash et al., 285 2012; Martin et al., 2012) produced by the Group for High Resolution Sea Surface Tem-286 perature (GHRSST) at Ifremer/CERSAT (France). These daily cloud-free SST maps 287 are obtained using an optimal interpolation on a global gridded at $1/10^{\circ}$ over the full 288 globe merging both microwave and infrared satellite SST. 289

290

3.3 Argo profiles data and eddy colocation

While altimeter measurements are representative of the vertically integrated effect 291 of variations in temperature and salinity over the whole water column, ADT maps do 292 not allow for directly obtaining the vertical hydrological structure of the water column. 293 To gain insights on this, we colocated the Agulhas Rings identified by TOEddies with 294 in situ observations obtained from vertical profiles of the Argo floats international pro-295 gram which started in 2000. Argo floats provide a large number of CTD (Conductivity, 296 Temperature, and Depth) vertical profiles (i.e. more than 1.5 million profiles) over the 297 upper 2000 m of the global ocean. These data are collected and made freely available 298 by the International Argo Program as part of the Global Ocean Observing System and 299 the national programs that contribute to it (doi: https://doi.org/10.17882/42182). 300 Argo Data Centers provide delayed mode data for each vertical profile. These data are 301 validated and calibrated by the data assembly centers (e.g., Owens & Wong, 2009; Ca-302 banes et al., 2016) against the most up-to-date global climatology (computed with both 303 full depth CTD from oceanographic research cruises and validated Argo floats) to esti-304 mate errors for each Argo profile. However, because mesoscale eddies can have the abil-305 ity to advect water from remote regions, the water trapped in the eddy core might have 306 a distinct hydrological signature with respect to the surrounding climatological environ-307 ment. Indeed, Argo profiles close to an eddy center significantly differ from the environ-308 ment (e.g., Chaigneau et al., 2011; Pegliasco et al., 2015). Therefore, in this study, we 309 use the Argo data downloaded from the Coriolis Global Data Center (Coriolis GDAC; 310 http://www.coriolis.eu.org) that are not in the delayed mode but with control qual-311 ity flags equal to 1 and 2, which refer to "good observation" and "probably good obser-312 vation". 313

Because data from Argo profiles are usually not recorded at constant pressure lev-314 els, we have built a homogeneous dataset by interpolating the temperature and salin-315 ity on a constant vertical grid of 10 m step. Furthermore, we applied an additional se-316 lection of Argo profiles, following Chaigneau et al. (2011) and Pegliasco et al. (2015), to 317 ensure the consistency of the interpolation. First, we kept a profile if it contained at least 318 one measure between the surface and 20 m and one below 1500 m. Then, we required 319 that the vertical distance between two consecutive measurements not exceed a given thresh-320 old, depending on the depth interval. These limits are 25, 50, 75, 100, and 200 m between, 321 respectively, the depth intervals 0-100 m, 100-300 m, 300-500 m, 500-1000 m, and be-322

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low 1000 m. This procedure removes about 40% of the profiles. Finally, we used the Gibbs SeaWater (GSW) Oceanographic Toolbox of the Thermodynamic Equation of SeaWater TEOS-10 (McDougall & Barker, 2011) to compute the recommended hydrological variables, which are the conservative temperature (CT), the absolute salinity (AS), and the potential density anomalies referenced to the ocean surface (σ_0).

When based on the Argo system, Lebedev et al. (2007)showed that every Argo float 328 moves, on average, about 4 km in 8 hours at the surface while sending 8 messages to the 329 satellite. Consequently, a typical lag of 1 hour can occur between the time the Argo float 330 reaches the surface and the time its position is recorded by an Argos satellite. This time 331 lag may induce an error in the position of the hydrological profile of the order of 500 m, 332 which is small compared to the typical radii of mesoscale eddies (Carton, 2001) as well 333 as the resolution of satellite altimetry from which eddy centers and shapes are identi-334 fied. It is therefore possible to determine if a given hydrographic profile is located inside 335 a detected eddy (e.g., Chaigneau et al., 2011; Pegliasco et al., 2015). The outer limit R_{out} 336 is used for this determination as the trapped water in the eddy is not expected to be lim-337 ited to the R_{Vmax} contour as previously discussed. 338

The colocation of Argo profiles and the TOEddies eddies results in the separation 339 of such profiles into three groups: those sampling a cyclonic eddy, those sampling an an-340 ticyclonic eddy, and those falling outside of either type. We define the latter as profiles 341 sampling the environment within which eddies propagate. In order to quantify the hy-342 drological anomalies associated with each eddy, we computed a climatological profile char-343 acteristic of the environment outside that eddy which is then subtracted from the ver-344 tical profile sampling the core of the eddy. The climatological profile is the average of 345 all the profiles measuring the environment outside the eddy. However, we require that 346 their position falls within a rectangular box of of $2.5^{\circ} \times 2.5^{\circ}$ centered on the eddy and 347 whose dates are within a maximum temporal range of 30 calendar days (i.e. indepen-348 dently of the year) from the date of the Argo profile sampling the eddy. We tested both 349 the spatial and time thresholds in order to find the best fit while keeping enough pro-350 files and being sufficiently restrictive by not considering different hydrological regions 351 or seasons to characterize the environment. Finally, we estimated the distance between 352 each profile and the geometrical center of the eddy. This distance from the center will 353 be referred as Dc in the rest of this article. 354

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355 4 Results

We followed Laxenaire et al. (2018) in creating the eddy network associated with 356 the Agulhas Ring identified in the South Atlantic Eddy Atlas. In that context, Agulhas 357 Rings are defined as the anticyclonic eddies which are initially detected in the South-358 east Indian Ocean and then enter and propagate into the South Atlantic. The limit used 359 to separate these two basins is an imaginary line connecting specific topographic struc-360 tures, such as the Agulhas Ridge that defines the southeastern limit of the Cape Basin 361 (1a). As shown by Dencausse et al. (2010), Agulhas Rings generally experience numer-362 ous mergings or splittings during their lifetime. Hence, several segments and bifurcations 363 of trajectories have to be associated to correctly depict the whole lifespan for these ed-364 dies. In what follows, we will make use of the concept of the Agulhas Ring Eddy Net-365 work (AREN) of trajectories introduced by Laxenaire et al. (2018). This includes all the 366 trajectories undertaken by any eddy, parent or descendant, that has merged with or split 367 from a particular eddy or group of eddies originating in the Indian Ocean and traveling 368 across the Indo-Atlantic limit. 369

The total AREN, defined during the period 1 January 2000 to 31 December 2016 (Laxenaire et al., 2018), is composed of 730 481 eddy occurrences (i.e. eddies detected in daily maps) that cluster into 6 363 trajectories. The percentage of time that each ADT grid point is inside the characteristic eddy contour of an eddy occurrence that is part of the AREN is presented in Figure 1b. The total AREN was sampled by 7 419 Argo profiles of which 826 sample Agulhas Ring main trajectories (i.e. a trajectory of an Indian anticyclone that flows into the South Atlantic basin).

Argo float No. 5902281 was identified as the one that was trapped for the longest 377 period by a single Agulhas Ring, providing 54 vertical profiles over the period from May 378 2012 to November 2013, during which it propagated from Cape Basin to the Mid-Atlantic 379 Ridge (Figure A1 in the Appendix). The long trapping of this Argo float suggests that 380 Agulhas Rings found in this region might behave as coherent eddies, at least at 1000 m, 381 which is the parking depth of these floats. This was also confirmed by other examples 382 of float trapping by such eddies described in the literature. In particular, Nencioli et al. 383 (2018) identified a comparable long trapping of an Argo float by an Agulhas Ring in this 384 area between February 2014 and August 2015. 385

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The AREN associated with the selected Agulhas Ring is presented in Figure 2. The 386 main trajectory, as defined by the cost function, is composed of segments 2, 5, and 6. The 387 network, composed of seven segments, is a general example representing the relatively 388 complex history of Agulhas Rings. It includes the various eddies and related segments 389 of trajectory that have merged with and split from this Agulhas Ring during the 4 years 390 and 7 months of its lifespan (from January 2011 to July 2015). Only the segments that 391 interact directly with the main trajectory that trapped the Argo float No. 5902281 are 392 discussed below. It is important to emphasize that, as the TOEddies Atlas could con-303 tain some spurious eddy merging and splitting events, we manually validated the par-394 ticular Agulhas Ring trajectory we analyze in this study by excluding eddies that ini-395 tially merge with and then split from this trajectory during times shorter than one week. 396 The various eddies associated with this Agulhas Ring trajectory were sampled in total 397 by 112 profiles from 19 different Argo floats. The number of the profiling floats together 398 with their complete trajectories are presented in Figure A1 in the Appendix. 399

The specific Agulhas Ring trajectory network that we analyze in this study starts 400 with the shedding at the Agulhas Retroflection of three independent Agulhas Rings. The 401 first shedding, which occurred on 8 January 2011, results in an eddy moving south and 402 entering the Cape Basin by crossing the Agulhas Ridge (dark blue, Segment 1 in Fig-403 ure 2) and following the Southern Agulhas Rings Route defined by Dencausse et al. (2010). 404 The second and third shedding occur, respectively, in August and November 2011. The 405 second shedding gives rise to an eddy whose trajectory (mid-blue, Segment 2 in Figure 2) 406 follows the Agulhas Rings Central Route (Dencausse et al., 2010), whereas the third one 407 (light blue, Segment 3 in Figure 2) takes the Northern Agulhas Rings Route (Dencausse 408 et al., 2010). These two trajectories merge together in the eastern part of the Cape Basin 409 forming Segment 4 of the AREN (green, Figure 2). The latter merges with the South-410 ern Route eddy (Segment 1) in the northwestern part of the Cape Basin close to the Walvis 411 Ridge. It results in Segment 5 (yellow line) that interacts with some other Agulhas Rings 412 and anticyclones along its route but without any consistent merging and splitting events 413 for 56 months until it reaches the South American Margin. There, in March 2015, it splits 414 into two eddies that move south along the American continental slope until they disap-415 pear from the satellite altimetry field in July 2015. 416

417

In this study, we focus on the period of time spanning May 2012 to November 2013, during which the Agulhas Ring did not merge or split while being relatively well sam-

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Figure 2. a) Geographical distribution of the segments (in colors) that comprise the network of trajectories for the Agulhas Ring sampled for the longest period by an Argo profiling float. The positions of the Argo profiles sampling the eddy core of the whole set of eddies that comprised this particular network are represented by the black crosses; b) A sketch displaying the various segments together with the eddy merging and splitting events and Argo profiles position as a function of time. The gray shading patches in (a) represent water depth shallower than 3500 m in the ETOPO2 dataset (Smith & Sandwell, 1997).

pled by multiple Argo floats (a profile sampled the structure at least every 10 days: see 419 the black crosses in Figure 2). The dataset combines 553 days of eddy detection from 420 ADT maps and 71 Argo vertical profiles located within the core of the eddy and achieved 421 by 14 different Argo floats. During this period, the anticyclone associated with Segment 422 5 leaves the Cape Basin, crossing the Walvis Ridge between October 2012 and January 423 2013; it then propagates in the eastern part of the South Atlantic before crossing the high-424 est points of the Mid-Atlantic Ridge between August and October 2013 (see Figure B1 425 in the Appendix). 426

427

4.1 Evolution of the Agulhas Ring surface dynamics

The temporal evolution of the surface signature of this Agulhas Ring (i.e. size and 428 surface intensity) computed by TOEddies from ADT maps is presented in Figure 3. While 429 R_{Vmax} of this eddy is rather constant during the entire period with a median value of 430 64 km associated with a small 8 km standard deviation (STD), R_{out} shows important 431 variations (between 75 and 150 km and a STD of 23 km). To emphasize these differences, 432 the evolution of the outer and characteristic contours (the latter is associated to V_{max}) 433 is presented in Figure 4. Each contour is drawn in the translating frame of the Agulhas 434 Ring where the position of the center of each figure corresponds to the center associated 435 to the extrema of ADT. The contrast between the highly variable structure of the outer 436 contour, which takes very complex shapes, and the characteristic contour, which remains 437 coherent and keeps a relatively circular shape during the whole period of study, appears 438 clearly. This difference might be due to the distortion of the edge of the eddy by the strain 439 of neighbor eddies and the external flow field in general or to the small signal-to-noise 440 ratio of the ADT outside of the eddy. In any case, we prefer to use the characteristic eddy 441 contour and the corresponding speed radius R_{Vmax} to estimate the size of the struc-442 ture, similarly to other algorithms (e.g., Nencioli et al., 2010; Duacs/AVISO+, 2017; Le Vu 443 et al., 2018). 444

The evolution of the monthly mean V_{max} and Ro is shown in the lower panels of Figure 3. The maximum value of V_{max} is about 50×10^{-2} m s⁻¹ in end of the austral fall 2012. It then decreases gradually to smaller values, below 20×10^{-2} m s⁻¹, almost one year later. Figure 3 shows a similar decay for Ro. This is very likely due to the variation of V_{max} as the eddy size is constant and the meridional displacement is limited. One might argue that this decrease in surface intensity is related to the change of en-



Figure 3. Temporal evolution of a) the monthly averaged equivalent radius of the outer contour (R_{out}) and the eddy-core contour where the azimuthal velocity is maximum (R_{Vmax});
b) the maximum azimuthal velocity (V_{max}); and c) the absolute Rossby number of the core (-Ro-) as derived from the altimetry maps. The error bars correspond to the monthly STD of these parameters.



Figure 4. a) Outer contours and b) characteristic contours (associated with the maximum azimuthal speed) in the referential of the Agulhas Ring at times when an Argo float samples it.

vironment. However, the amplitude of the Agulhas Ring decreases from 0.4 m to 0.1 m 451 (not shown) during its journey while the variations of the MDT interpolated at the Ag-452 ulhas Ring center do not exceed 0.1 m. A similar decay of surface intensity across the 453 South Atlantic has already been documented by several authors (e.g., Byrne et al., 1995; 454 Schouten et al., 2000; Guerra et al., 2018; Laxenaire et al., 2018). During the whole pe-455 riod, the Agulhas Ring absolute Ro remains small (below 0.1), which confirms that this 456 eddy is balanced geostrophically and therefore we do not need to apply the cyclo-geostrophic 457 correction as in Ioannou et al. (2017). A short period of intensification is visible in win-458 ter during July and August 2013 and a final decay of the surface signature is visible dur-459 ing the two last months of the period under study. 460

461

4.2 Evolution of the internal structure

In order to estimate the evolution of the conservative temperature (CT), absolute salinity(AS) and potential density (σ_0) inside the Agulhas Ring, we first divided the time period into 10-day intervals. For each of these 10-day intervals we selected the Argo profiles closest to the eddy center. The selected vertical profiles are presented in the left panels (a, c, and e) of Figure 5 and the associated anomalies, computed as the difference between the vertical profiles sampling the eddy and the mean environmental profiles, are presented in the right panels (b, d, and f) of the same Figure together with the distance
(Dc) of the Argo profile from the eddy center.

The climatologic profiles used to compute the anomalies as well as the number of 470 profiles used to compute the first 1500 m of each climatological profile at each time step 471 are presented in Figure 6. For this study we selected only Argo profiles associated with 472 a maximum depth of over 1500 m. Indeed, the number of profiles sampling the upper 473 layer of the water column is higher than those reaching depths of over 1500 m. The min-474 imum available profiles within the eddy core close to the surface is 40, but this decreases 475 to 28 for profiles reaching a depth of 1800 m (not shown). The maximum number of pro-476 files is 118 for the upper 1500 m of depth, and 93 for profiles reaching 1800 m (not shown). 477 In the climatological profiles, the upper 200 meters appear as the most variable. A sur-478 face layer of low density appears in October 2012 concomitant to the onset of the sum-479 mer seasonal stratification as well as the drifting of the eddy into warmer waters. This 480 limit, characterized by the isopycnal 26.2 kg m^{-3} , appears to continuously thicken dur-481 ing a period of more than a full year. The layers below this isopycnal show more steady 482 characteristics during the full period, albeit a relatively small downlift of the isolines ap-483 pears between a depth of 200 and 400 m and an uplift appears below 400 m. Very likely, 484 this is due to the westward thinning of the Antarctic Intermediate Water (AAIW) layer 485 marked by a minimum of salinity around 1000 m as discussed by Rusciano et al. (2012). 486

Figure 5 presents the hydrological characteristics of the Agulhas Ring as provided 487 by the Argo profiles sampling the eddy. It shows that important variations in the eddy 488 properties occur in the upper 200 m. Here, a shallow and low-density layer (limited by 489 the 26 kg m⁻³ isopycnal) is visible in May 2012 (during the end of the austral fall). This 490 layer is eroded at the beginning of the austral winter (from June 2012) and reappears 491 in October 2012 during the austral spring. This layer might be associated with the sea-492 sonal cycle, with the formation and erosion of a seasonal thermocline. However, simi-493 larly to the behavior shown by the climatological profiles (Figure 6), this layer contin-494 ues to thicken from October 2012 to November 2013, not showing any further winter ero-495 sion. This suggests that the upper eddy layer not only evolves with the seasonal cycle 496 but is also affected by the displacement of the eddy into a different hydrological region 107 (the South Atlantic subtropical gyre) characterized by a shallow permanent stratifica-498 tion. 499



Figure 5. a) Conservative temperature, b) conservative temperature anomaly, c) absolute salinity, d) absolute salinity anomaly, e) potential density, and f) potential density anomaly for the closest Argo profiles to the Agulhas Ring center for each 10-day interval as a function of time and depth. Black lines with markers in each right panel represent the distance of each profile from the eddy center (Dc) whose scale is presented on the y-axis on the right of panels b, d and f. The marker is a cross for profiles inside the characteristic contours; otherwise it is indicated as a square. Selected isotherm, isohaline, and isopycnal levels are added to the corresponding panels for both the full fields and the anomalies.



Figure 6. a) Conservative temperature, b) absolute salinity, and c) σ_0 for the environment climatological profiles we used to compute the Agulhas Ring vertical property anomalies in Figure 5; d) Number of averaged Argo profiles used to to compute the first 1500 m of the environment climatology.

The Argo data also show a relatively high correlation between vertical properties 500 and the distance (Dc) of the profile from the eddy center (see, for instance, the varia-501 tions of Dc together with those of the isolines 10° C, 34.7 g kg⁻¹, and 27 kg m⁻³ in Fig-502 ure 5a,d,e). As expected for a warm and salty core anticyclone such as an Agulhas Ring, 503 the isolines are deeper near the center of the structure than at its edges. The correla-504 tion among the eddy hydrological properties and Dc is particularly evident from the ver-505 tical CT, AS, and σ_0 anomalies (Figure 5b,d and f). Their amplitude variations are in-506 deed intimately linked with Dc variability and this through the whole water column. In 507 particular, Figure 5b,d and f show clearly a strong reduction in the anomaly amplitude 508 when Dc is larger than 65 km. This corresponds to the periods June-July 2012, Octo-509 ber 2012, January 2013 and, later on, in August and October 2013. 510

The eddy property anomalies (Figure 5b,d and f) show that the Agulhas Ring is 511 warmer, saltier and less dense than the environment. A marked positive anomaly in AS 512 $(> 0.2 \text{ g kg}^{-1})$ and CT $(> 1^{\circ}\text{C})$ down to at least 800 m appears clearly for small Dc (Dc 513 < 50 km). Moreover, these anomalies exhibit a striking vertical pattern characterized, 514 from November 2012 to August 2013, by two well-separated extrema roughly located at 515 a depth of -350 m and -650 m. Such a vertical structure strongly suggests the presence 516 within the eddy of two cores of water masses very different from the environment. It should 517 be noted here that σ_0 anomaly for the two distinct water-mass cores is about -0.3 kg m⁻³, 518 a value six times higher than the STD of the environment σ_0 (0.05 kg m⁻³ (not shown)). 519 It is worth noting that, after November 2012, negative anomalies of AS are found within 520 the eddy below 1000 m. 521

To better understand the vertical structure of the Agulhas Ring, we plotted the Brunt Väisälä frequency squared N² in the Argo profiles plotted in Figure 5, and the climatological environment in Figure 7. N² is computed from equation 4, where g is the gravitational acceleration and ρ_0 the density of reference set to 1000 kg m⁻³.

$$N^2 = \frac{-g}{\rho_0} \frac{\partial \rho}{\partial z} \tag{4}$$

The environment profiles exhibit a seasonal cycle characterized by the development of a winter mixed layer (low values of N², below 1×10^{-5} s⁻²) extending, on average, to a depth of 150 m in August-September (Figure 7b). On the other hand, the eddy core is characterized by a considerably deeper mixed layer which develops during the first five



Figure 7. Time evolution of the Brunt Väisälä frequency squared computed for the Argo float No. 5902281 profiles a) within the Agulhas Ring, and b) for the environment climatology. Isopycnal levels separated by a 0.5 kg^{-3} interval are added to the corresponding panels.

months of the time series and which reaches a depth of 350-400 m in August-September 530 2012. During this period, the eddy upper layers are connected to the sea surface and the 531 atmosphere through this deep mixed layer. Later on, from October 2012 to March 2013, 532 the summer restratification seems to isolate the eddy homogeneous cores from the sur-533 face and prevent any direct heat or momentum transfer between the eddy core and the 534 atmosphere.. Below this layer lies the uppermost of the two cores whose properties cor-535 respond to the previous winter mixed layer. Its properties are homogeneous over more 536 than 200 m, suggesting that this core belongs to MWs. 537

Figures 5 and 7 suggest, therefore, that the main hydrological core of the eddy 538 was connected with the sea surface and exposed to air-sea interactions during the first 539 part of the time series and that it became a subsurface core, isolated by the presence of 540 an upper stable and relatively thick (200 m) warm layer, while leaving the Cape Basin 541 and entering the South Atlantic Ocean by crossing the Walvis Ridge (see Figure 2). This 542 analysis is, of course, restricted by the limited availability of profiles close to the eddy 543 center before July 2012. To corroborate our results, we undertook a satellite SST data 544 analysis to try to assess the surface signature of the eddy and to characterize its connec-545 tion with the ocean surface layer in an independent way. This is in line with the works 546 of both Assassi et al. (2016) and (Schütte et al., 2016), who used surface SST anoma-547

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lies to discriminate surface and subsurface intensified eddies. Indeed, anticyclonic eddies
are associated with positive Sea Level Anomalies. If they are surface eddies, they are expected to correspond to positive SST anomalies, whereas if they are subsurface eddies,
they should be associated with negative SST anomalies as a consequence of the doming
of the isotherm above their hydrological core.

For this purpose, we used the ODYSSEA SST dataset (Dash et al., 2012; Martin 553 et al., 2012) that we have interpolated at the position of the eddy center during the pe-554 riod of interest (see Figure 8). For each date, we computed the average of the SST field 555 for all the points in the square box area of $300 \text{ km} \times 300 \text{ km}$ centered on the eddy cen-556 ter (i.e. 150 km corresponds to the maximum R_{out}). The anomalies are computed by 557 subtracting this mean SST from the SST value at the center of the eddy. These anoma-558 lies are presented in Figure 8. It appears from this figure that they change sign between 559 September and October 2012. This is in accordance with what we identified as the be-560 ginning of the isolation of the Agulhas Ring from the ocean surface, as previously dis-561 cussed in the analysis of Figures 5 and 7. Such a change of sign can be due to the mod-562 ification of the background environment while the eddy moves into subtropical waters. 563 Yet, the absolute SST (blue line in Figure 8) clearly shows a seasonal cycle as well as 564 an interannual increase, indicating that variations also occurred within the eddy. It is 565 not consistent with a fixed patch of constant temperature drifting into another environ-566 ment. However, J. Souza et al. (2014) discussed the presence of negative SST anoma-567 lies in relation to Agulhas Rings still connected with the ocean surface. They explained 568 this by a modification of the Ekman pumping due to the presence of the eddy and that 569 it may induce dipole SST anomalies with the center of an Agulhas Ring associated to 570 a negative SST anomaly, whereas a positive anomaly would correspond to the eddy bound-571 aries. 572

To assess the geographical pattern of SST anomalies, we computed monthly SST 573 anomaly maps in the moving frame of the Agulhas Ring. They are presented in Figure C1 574 in the Appendix. These maps show that, in July 2012, the Agulhas Ring core is asso-575 ciated with positive SST anomaly values. These, however, are lower within the eddy's 576 inner core than at its boundaries, which might confirm the conclusions of J. Souza et al. 577 (2014). However, after October 2012, the date we identified as that corresponding to the 578 isolation of the main hydrological core of the Agulhas Ring from the ocean surface, the 579 SST dipole-like anomaly disappears and the Agulhas Ring becomes associated with a 580

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strong patch of negative SST anomalies, confirming the subsurface nature of the eddy following critera of Assassi et al. (2016) and (Schütte et al., 2016). Positive anomalies still exist close to the eddy boundary but are localized at the eddy western side, a feature that can be explained by the stirring of the environment due to the anticlockwise rotation of the Agulhas Ring in the presence of a north-south gradient of temperature.

The results we obtained by analyzing two independent datasets (Argo vertical pro-586 files and satellite SST) corroborate the finding that the main hydrological core of the Ag-587 ulhas Ring, initially connected to the surface, subducted into the ocean interior while 588 leaving the Cape Basin and penetrating into the South Atlantic subtropical gyre. We 589 follow here Williams (2001)'s definition of subduction as the transfer of fluid from the 590 mixed layer to the stratified thermocline (i.e. below the seasonal mixed layer). It is clear 591 that the winter mixed layer developing between March 2013 and September 2013 stays 592 separated from the shallower eddy core of homogeneous water. However, it is difficult 593 to select the main process generating the observed subduction. Indeed, the observed be-594 havior might result from a modification of the eddy upper-layer waters by ocean-atmosphere 595 interactions Arhan et al. (2011) as well as by the lateral penetration of an eddy below 596 the lighter upper water of the South Atlantic subtropical gyre. 597

In order to gain insight into this question, we evaluated (Figure D1 in the Appendix) 598 the differences in terms of T-S properties for Argo profiles sampling segment 5 during 599 the period November 2012 to November 2013 near the eddy center (Dc < 25 km, in red 600 in Figure D1) and those close to the eddy boundaries (150 < Dc < 200 km), in blue in 601 Figure D1). This analysis shows that the upper-layer eddy water masses are different 602 to those of the environment. However, the eddy upper-water velocities still verify the eddy-603 coherent condition defined by Flierl (1981) and used in many studies since then [(e.g., 604 Chelton et al., 2011): the minimum of V_{max} is larger than 0.2 m⁻¹ (see Figure 3) while 605 the drifting speed of the eddy does not exceed 0.1 m s⁻¹. This suggests that the observed 606 subduction could result from the surface modification of the Agulhas Ring advected wa-607 ter. Using a very high-resolution numerical simulation in the Cape Basin, Capuano et 608 al. (2018) showed that submesoscale instabilities (of different type) determine, in win-609 ter, the formation of deep mixing layers in Agulhas Rings and, in summer, induce an in-610 tense upper-layer restratification. As the Agulhas Ring moves westward exiting the Cape 611 Basin, it enters a region of milder air-sea interactions that are not sufficiently strong to 612



Figure 8. Sea Surface Temperature (blue) and associated anomalies (red) interpolated from the ODYSSEA SST dataset (Dash et al., 2012; Martin et al., 2012) at the center of the Agulhas Ring. The anomalies are computed by subtracting the mean SST (computed as the average of the SST in the square box area of 300 km \times 300 km centered on the eddy center) to the SST value in the center of the eddy. All the data were smoothed by a moving average associated with a monthly window.

- erode the upper-layer stratification. Such a process might explain the isolation of the Agulhas Ring subsurface core from the ocean surface.
- Figure 7 reveals the presence, between October 2012 and August 2013, of a sec-615 ond, albeit thinner, homogeneous layer located deeper than the first one (between 500 616 and 600 m). It corresponds to the second thermohaline anomalies core that appears in 617 the Argo vertical profiles sampling the Agulhas Ring (Figure 5). After August 2013, the 618 Argo profiles sample the eddy farthest from the eddy center. This prevents any conclu-619 sion as to what makes this deeper core of MW disappear. Indeed, on August 2013, the 620 eddy is located over the Mid-Atlantic Ridge (see Figure B1). We suggest that the inter-621 action between the eddy and the topography caused an intense mixing at depth with neigh-622 boring waters. Or, it might be that, because of the larger distance of the sampled pro-623 files from the eddy center after August 2013, this core of MW that was probably small 624 in its lateral extent was not sampled by the Argo floats. 625



Figure 9. a) Argo vertical profiles of density anomaly. Four lie close to the eddy center and show the two mode waters' thermohaline extrema (solid lines); one is located farther away (dashed lines) and does not display these two mode waters' related extrema. b) Depth of the two mode water cores as a function of Dc for all the profiles lying at less than 40 km from the eddy center. An outlier is identified if both extrema in a profile are at a distance from the black lines greater than the STD associated with the determination of each extremum.

To prevent the interference of the varying position of Argo floats while attempt-626 ing to determine the eddy evolution in time, we select, in the following section, only those 627 Argo profiles located within the eddy core (i.e., $Dc < R_{Vmax}$). The density anomalies 628 associated with four profiles separated by four or five months between June 2012 and 629 August 2013 are shown as solid lines in Figure 9a. All these profiles are located inside 630 the eddy and close to its center (15 km < Dc < 30 km), albeit it is worth mentioning 631 that accuracy in determining the eddy center from ADT maps is limited and this might 632 induce significant errors in Dc estimates. For comparison, Figure 9a presents, in a dashed 633 line, a vertical profile undertaken in January 2013 by an Argo float far from the eddy 634 center (Dc = 151 km). From this figure, it appears clearly that this profile does not sam-635 ple any of the eddy MW cores. 636

Figure 9b shows the depth of the two Agulhas Ring MW cores as a function of Dc computed by taking a large number of Argo profiles, all located near the eddy center (Dc < 40 km) and defined as the vertical maxima of thermohaline anomalies. The vertical location of the two thermohaline anomaly maxima varies weakly with time and with the distance of the Argo profile from the eddy center. We also computed the STD of the residual between each extremum and the linear regression obtained between Dc and the depth

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of the two anomaly peaks. We considered as outliers those profiles whose residuals are
larger than the STD (Figure 9b). From this, it appears that two of the three profiles
that sampled the eddy before it subsided below the surface in November 2012 differ significantly from the others. For the latter, the density anomaly of the core seems to keep
roughly the same depth for several months.

648

4.3 Reconstruction of the subsurface structure of an Agulhas Ring

Figures 5 and 7 show that, from November 2012 to November 2013, the upper 150 m layer of water within the Agulhas Ring limits was characterized by a strong seasonal variability, whereas below it, the thermohaline properties underwent only small variations. We therefore assumed, as a first-order approximation, that the Agulhas Ring below a depth of 150-200 m was in a quasi-steady state, and that the upper 150 m layer of water no longer belonged to the eddy main hydrological core.

Similarly to the assumptions of J. M. A. C. Souza et al. (2011) and Nencioli et al. 655 (2018), we also hypothesized that the eddy had a quasi-circular symmetry. The ampli-656 tude of the subsurface anomaly will then depend only on the distance (Dc) between the 657 Argo float position and the geometrical eddy center. As discussed previously, R_{Vmax} 658 can be considered to be constant during at least the period November 2012 to Novem-659 ber 2013 (with a median and mean radius of 63 km and a STD of 8 km). However, to 660 test the validity of a quasi-circular eddy assumption, we estimated the ellipticity (ϵ) of 661 the characteristic eddy contours derived from the daily ADT maps, from equation 5 where 662 a is the semi-major and b the semi-minor axis. 663

$$\epsilon = 1 - \frac{b}{a} \tag{5}$$

The ellipticity remains small from November 2012 to November 2013, with a median value of 0.11, a mean of 0.12 and a STD of 0.07. We therefore restricted our analysis to this 12-month period to ensure the validity of the axisymmetry hypothesis for the eddy, which would otherwise not be valid for large ellipticity values.

In order to reconstruct the Agulhas Ring axisymmetric structure, we used 71 Argo profiles that were located within a distance of 185 km (i.e. $^{3}\times R_{Vmax}$) from the geometrical eddy center (Figure 10) during the November 2012 to November 2013 period.



Figure 10. Position of the Argo profiles in the moving frame of the Agulhas Ring. The center of the frame corresponds to the centroid of the characteristic eddy contour delimited by R_{Vmax} and computed from ADT maps. The filled circles indicate Argo profiles inside the characteristic eddy contour, the gray circles those inside outer eddy edge, and the empty diamond those outside the Agulhas Ring and any other neighboring eddy and lying at a 160 km radius from the Agulhas Ring center.

The Argo float No. 5902281 sampled more than 54% of the profiles, whereas other floats surfaced sporadically inside the eddy. Overall, during the given 12-month period, the Agulhas Ring was sampled by 52 profiles within a distance of 100 km from the eddy center.

Different techniques have been used in the literature to attempt a reconstruction of the vertical structure of mesoscale eddies from sparse *in situ* observations. Most of them employed a composite eddy reconstruction approach (e.g., Schütte et al., 2016; Amores et al., 2017), while others tried to recover the structure of specific eddies. For example, Chaigneau et al. (2011) objectively mapped observations onto a 10-km grid assuming an isotropic Gaussian covariance decorrelation scale of 100 km, and J. M. A. C. Souza et al. (2011) fitted to a 7th order one-dimensional Lagrange polynomial. However, the

-30-

Gaussian method smooths out horizontal gradients, whereas high-order polynomials of ten induce an overshooting of the hydrological variables at the outer edge of the reconstructed eddies. To avoid these drawbacks, we used a generic function tending towards zero outside the eddy.

The generic function we used to fit the (CT, AS) anomalies we defined previously 686 at each depth (see equation 6) is that of an α -Gaussian vortex (see for example Carton, 687 2001; Le Vu et al., 2018; Zeitlin, 2018). The parity of this generic function ensures the 688 axisymmetry of the reconstructed eddy and an exponential reduction in its anomalies 689 far from the center. The $A_0(z)$ profile represents the maximal core anomaly inside the 690 eddy. To suggest a first guess for $A_0(z)$, we use the mean of the three Argo profiles clos-691 est to the eddy center while the parameters α and $R_0(z)$ are set initially to 2 (i.e. a purely 692 Gaussian shape as used by Nencioli et al. (2018)) and $\mathrm{R}_{\mathrm{Vmax}}=63~\mathrm{km}$ respectively. Then, 693 the three parameters $(A_0, R_0 \text{ and } \alpha)$ associated with the generic function 6 are adjusted 694 at each depth level, minimizing the residuals between the fitting of the equation and the 695 observations using the Trust Region Reflective algorithm (Branch et al., 1999) with the 696 function lsqcurvefit of the MATLAB Library. As we expect the anomalies to increase 697 toward the center, we do not allow A_0 to be lower than the first guess which ensure to 698 preserve the large scale gradient. Moreover, it is worth noting that the Trust Region Re-699 flective algorithm can stop at local best fit thus several adjustments are run at each lev-700 els varying the initial guess of α and $R_0(z)$ to detect the global best fit. Below 200 m, 701 the values obtained for the various parameters by fitting the function 6 are between 1.9 702 and 2 with a STD between 0.05 and 0.15 depending of the variable. Similarly, mean R_0 703 is between 66 and 76 km with a STD ranging between 10 and 17 km. 704

$$Anom(r,z) = A_0(z)e^{-\frac{1}{\alpha}\left(\frac{r}{R_0(z)}\right)^{\alpha}}$$
(6)

Finally, to obtain a first estimation of the thermohaline structure of the Agulhas Ring (Anom(r, z)), we added the average of all the profiles of the environment computed for each vertical level to the reconstructed anomalies.

Figure 11 shows the isolines of CT, AS, and σ_0 for the reconstructed Agulhas Ring (defined with the acronym RecAR from here on), superimposed over the raw Argo profile data plotted as a function of Dc. A more detailed examination of the σ_0 reconstruc-



Figure 11. Superposition of the observed (background color) and the reconstructed (black contours) Agulhas Ring of the a) conservative temperature, b) absolute salinity, c) σ_0 , and d) root-mean-square error between the observed σ_0 anomalies and the reconstructed values computed at each depth.

tion is shown in Figure E1 in the Appendix. Both figures show, below the surface, a particularly good agreement between the isocontours of RecAR and the raw Argo data.

Figure 11 shows clearly two layers of homogeneous thermohaline properties. A first 713 one is centered around a depth of 250 m, between the isolines $17^{\circ}C - 15^{\circ}C$, 35.9 g kg⁻¹ 714 - 35.7 g kg⁻¹, and 26.1 kg m⁻³ - 26.3 kg m⁻³. The maximal thickness of this layer is 715 350 m at the eddy center. The second homogeneous layer is centered at a depth of 500 716 m, and it is characterized by the isoline intervals 13° C - 11° C, 35.5 g kg⁻¹ - 35.3 g kg⁻¹, 717 and 26.5 kg m⁻³ - 26.7 kg m⁻³. One can observe that the depths of these cores do not 718 correspond to those obtained from anomalies in Figure 9 but correspond well with the 719 position of the N^2 cores at the end of the time series in Figure 7. Our impression is that 720 the position of the maximum anomaly shows the depths of the bottom of each layer of 721 MW just above the compensation that occurs below each MW. Consequently, the anoma-722 lies cannot be used to identify the center of a hydrological core. 723

In order to test the accuracy of the three-dimensional reconstruction, we computed the root mean square (RMSE) of the difference between the *in situ* measurements provided by every Argo profile and RecAR (Figure 11d). The values of RMSE vary between 0.01 and 0.05 kg m⁻³, which is six times less than the maximum σ_0 anomalies. This gives us confidence in the eddy properties reconstruction.

The two local maxima at depths of 400 and 700 m in Figure 11 correspond to the 729 region of strong variation of properties when moving from the eddy center outward along 730 an constant line of depth. However, near the surface the errors are considerably larger. 731 The RMSE value of 0.05 kg m⁻³ lies between a depth of 150 and 160 m whereas the largest 732 RMSE value (0.2 kg m^{-3}) is found at 60 m. At these depths waters undergo a strong 733 seasonal forcing and therefore we cannot consider that the thermohaline properties of 734 the eddy remain constant here for the whole year. As discussed previously, the Agulhas 735 Ring has subducted below the subtropical gyre upper 150 m of warm waters. Hence, we 736 assume that the eddy upper limit is below this layer. We choose as such a limit for Re-737 cAR a specific isopycnal - the 26.2 kg m⁻³ isopycnal - which corresponds to the specific 738 limit identified in Figure 5 as the separation between the part of the water column that 739 evolves over time and the one which is steady below it, rather than a fixed depth. It is 740 important to note here that the depth of this isopycnal varies between 150 m near the 741

eddy center and 170 m away from it. In what follows, we will consider as RecAR the waters lying below the 26.2 kg m⁻³ isopycnal surface.

By using RecAR as the reference, we computed the error associated with the val-744 ues of Dc obtained in colocating the Argo profiles with the eddy as detected by the TOEd-745 dies algorithm. A distance is computed between each observation on the σ_0 levels, be-746 tween a depth of 200 m and 1000 m, from the Argo profiles and the corresponding value 747 in the RecAR. This corresponds to the distance between each observation and the Re-748 cAR isoline taken at the same depth as shown in Figure E1 in the Appendix. The lower-749 limit depth of 1000 m was fixed as the horizontal gradient of σ_0 is weak below this depth. 750 This would have impacted the accuracy in the determination of Dc. From the 66 pro-751 files, we computed mean values of this distance equal to 16 km associated with a STD 752 of 8 km. 753

Figure 12 shows the CT, AS, and σ_0 anomalies of RecAR as well as the Brunt Väisälä 754 frequency squared (N²). Such reconstruction clearly shows a dual core structure for Re-755 cAR. This is particularly discernible from the two low stratification layers in Figure 12d. 756 The anomalies are important as they materialize the eddy content and transport of proper-757 ties, such as heat and salt. The upper core lies at 350 m with peak anomalies of 3.7°C . 758 0.56 g kg^{-1} , and -0.35 kg m^{-3} for, respectively, conservative temperature, absolute salin-759 ity and potential density. The lower core lies at a depth of around 550 m and is char-760 acterized by anomalies of 4.4° C, 0.62 g kg^{-1} , and -0.31 kg m^{-3} . The anomalies of con-761 servative temperature and absolute salinity are more intense within the lower core but, 762 due to their inverse effect on density, the density anomalies are nearly equal for both cores. 763

In order to estimate the three-dimensional velocity structure (i.e. V(r, z)) for RecAR we use the non-linear thermal wind equation 7 (e.g., Ioannou et al., 2017):

$$\frac{1}{r}\frac{\partial V^2}{\partial z} + f\frac{\partial V}{\partial z} = \frac{-g}{\rho_0}\frac{\partial \rho}{\partial r}$$
(7)

To solve this partial differential equation, the velocity field is set to 0 at a depth of 1800 m (i.e. V(r,z = -1800) = 0). The resulting velocity field is shown in Figure 13a. The maximum value of the azimuthal velocity is equal to 31×10^{-2} m s⁻¹. It is located at a depth of 200 m and at a distance of 63 km from the eddy center. This value is very close to the mean maximum speed radius, $R_{Vmax} = 64$ km, estimated from the surface



Figure 12. Anomalies of a) conservative temperature, b) absolute salinity, c) σ_0 , and d) Brunt Väisälä frequency squared (N²) for the reconstructed Agulhas Ring. Contours in d) are isopycnals of the reconstructed Agulhas Ring. The gray patch near the surface in each panel corresponds to the region above the isopycnal surface 26.2 kg m⁻³, which marks the separation between the subtropical gyre upper warm waters and the eddy upper limit.


Figure 13. a) Velocity field of the reconstructed Agulhas Ring computed from hydrographic data and b) evolution of the geostrophic currents derived from satellite altimetry maps as a function of the distance from the center. The black line in b) is the velocity derived from hydrographic data at -200 m (i.e. where this velocity is at its maximum). A dashed white line is added at this depth in panel a). The black line in panel a) corresponds to the separatrix where the velocity is equal to 5.7×10^{-2} m s⁻¹ which is the median translation speed during the period November 2012 to November 2013. The dashed lines indicate the \pm one STD ($\pm 1.4 \times 10^{-2}$ m s⁻¹) limits of the separatrix. The gray patch in panel a) corresponds to the region above the isopycnal surface 26.2 kg m⁻³, which marks the separation between the upper subtropical gyre waters and the upper limit of the eddy.

 $_{771}$ geostrophic velocity field during the 12-month period. In comparison to the grid resolution of ADT maps (1/4 °), this difference in values is negligible.

In order to estimate the limits of the volume of water trapped within RecAR, we followed Flierl (1981) defining the volume of trapped water in an eddy as the envelope of depths enclosed within the outer eddy limit where the azimuthal speed is equal to or higher than the translating speed of the eddy. For that, we computed the translation speed of the eddy during the period of time of interest using the trajectory of the geometrical center of the eddy computed by TOEddies. The resulting median translation speed is 5.7 with a STD of 1.4×10^{-2} m s⁻¹.

We then identified the line delimiting the trapped water inside RecAR (called separatrix here, following De Steur et al. (2004)) by hypothesizing that the eddy is circular and is moving at a constant speed. The black solid line in Figure 13a indicates the ⁷⁸³ approximate location of the separatrix at each depth and the two black dashed lines de-⁷⁸⁴ limit the STD $(1.4 \times 10^{-2} \text{ m s}^{-1})$ of the mean translation speed. The separatrix is located ⁷⁸⁵ below a depth of 1000 m and at less than ~100 km from the eddy center. It should be ⁷⁸⁶ noted here that 1000 m is the parking depth for most of the core Argo floats. The fact ⁷⁸⁷ that the eddy is coherent at this depth explains why the Argo float No. 5902281 remained ⁷⁸⁸ trapped within the structure for so long.

We also compared the steady horizontal velocity structure of RecAR with the eddy 789 evolving surface geostrophic velocities derived from satellite altimetry. Figure 13b shows 790 the various surface geostrophic velocity profile derived from satellite altimetry and pro-791 vided by AVISO (in colors, starting in November 2012 with the blue color and ending 792 in Oct. 2013 with the red color) as well as the velocity profile at a depth of 200 m (black 793 solid line). The latter corresponds to the white dashed line in Figure 13a and depicts the 794 position at which the azimuthal velocities reach a maximum. During the period of time 795 in question, the V_{max} derived from satellite altimetry decreased with time from 35×10^{-2} 796 m s⁻¹ to 15×10^{-2} m s⁻¹ while R_{Vmax} remained approximately constant (Figure 3a). 797 Therefore, in less than a year, the surface geostrophic velocity corresponding to the eddy 798 position dropped to half the value of the mean RecAR subsurface geostrophic velocity 799 intensity. Given the large extent of the Agulhas Ring (both horizontally and vertically) 800 and its intense thermohaline signature, we suggest that the observed decrease in the sur-801 face velocity is not due to a mechanism of dissipation of the eddy, but to the decorre-802 lation of the structure main core from the upper water layer attributable to its subduc-803 tion during the Fall of 2012. This is confirmed by the hydrological anomalies near the 804 ocean surface being of opposite sign to those in the eddy subsurface core, as suggested 805 by Assassi et al. (2016) and Schütte et al. (2016). As a consequence, the surface layer 806 has an inverse effect on the vertically integrated properties (such as dynamic height, the 807 eddy geostrophic velocity, etc) compared to that of the eddy at its core. This can ex-808 plain, at least partially, the observed decrease in such variables observed since the sub-809 duction of the Agulhas Ring. 810

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4.4 Integral properties of the subsurface Agulhas Ring

We used the separatrix and the 26.2 kg m⁻³ isopycnal surface to identify both the eddy lower (z_s) and upper (z_0) limits to compute the RecAR volume. This amounts to $7.1 \times 10^{13} \pm 1.5 \times 10^{13}$ m³ where the confidence interval is computed using the STD of the eddy translation speed (as it impacts the volume integration). The temperature and salinity anomalies integrated between z_s and z_0 for both the Argo profiles and RecAR are presented in Figure 14. Here, again, a clear relationship appears between these values and the distance (Dc) from the eddy center. Moreover, the anomalies computed for RecAR and directly from the Argo profiles are in strong agreement, which supports our results and methodology.

$$HCA = 2\pi \int_0^{R_s} \int_{z_s}^{z_0} \rho C_p \Delta Tr d_r d_z \tag{8}$$

$$SCA = 2\pi \int_0^{R_s} \int_{z_s}^{z_0} \rho \Delta Sr d_r d_z \tag{9}$$

We estimated the eddy anomalies of heat (HCA) and salt (SCA) from the temper-821 ature and salinity anomalies we computed for RecAR and by integrating equations 8 and 9 822 where $C_p(T)$ is the heat capacity, $\rho(r, z)$ the density, $\Delta T(r, z)$ the conservative temper-823 ature anomalies and $\Delta S(r, z)$ the absolute salinity anomalies of RecAR, whereas $R_s(z)$ 824 is the radius of the separatrix. It is then possible to integrate, along the vertical, such 825 anomalies to assess the total integrated HCA and SCA for RecAR. The values we ob-826 tained were, respectively, $2.5 \times 10^{20} \pm 1.3 \times 10^{19}$ J and $6.\times 10^{12} \pm 1.2 \times 10^{11}$ kg where \pm in-827 dicates the STD. 828

To be able to compare to simpler estimates not depending on a precise determi-829 nation of the eddy volume defined by the separatrix, we integrated the RecAR temper-830 ature and salinity anomalies from depths of 1800 to 150 m over the 200 km area around 831 the eddy center. The values we obtained were 2.9×10^{20} J for HCA and 4.8×10^{12} kg for 832 SCA. The estimates obtained by the two approaches are very close for HCA whereas they 833 differ significantly for SCA. This is very likely due to the presence of a negative patch 834 of AS anomalies not taken into account in the estimates obtained from the first approach 835 as this patch lies below the eddy trapping depth (Figure 12b). 836

Finally, the instantaneous volume, heat, and salt transport anomalies are computed following the method introduced by Olson and Evans (1986) and also used by A. M. Doglioli et al. (2007). These physical quantities are obtained by multiplying the integrated eddy properties with the translation speed divided by the diameter of the structure. They account for the transport generated by an eddy crossing an imaginary section. For the

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Figure 14. Anomalies of a) Heat Content and b) Salt Content as a function of the distance from the eddy center derived for both the reconstructed Agulhas Ring and the Argo profiles sampling the eddy. These values are obtained by integrating equations 8 and 9 vertically from the eddy separatrix up to 200 m.

purposes of calculating transport values, the radius of the volume section was identified 842 as that of the separatrix that reached the 26.2 kg m^{-3} isopycnal surface. This criteria 843 led to a radius of 180km. The resulting volume, heat, and salt transports STD are, re-844 spectively, 6 \pm 0.5 Sv, 0.02 \pm 0.004 PW, and 5.5 $\times 10^5 \pm$ 1.4 $\times 10^5$ kg $^{-1}.$ These values are 845 large as they correspond to the instantaneous transport of an Agulhas Ring. However, 846 they cannot be used to compare directly with most estimates given in the literature as 847 these assess the generic impact of Agulhas Rings by dividing the volume, heat, and salt 848 contents of each eddy by the number of seconds in one year (e.g., van Ballegooyen et al., 849 1994; Garzoli et al., 1999). By using this generic approach, the transport of volume, heat, 850 and salt would amount to, respectively, 2.2 Sv, 8.0×10^{-3} PW, and $2.2\times10^{5}~{\rm kg~s^{-1}}.$ 851

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5 Comparison with Agulhas Rings identified in the literature

For more than two decades, numerous Agulhas Rings have been sampled by *in situ* data. In this section, we compare the subsurface properties of RecAR with 27 different of those Agulhas Rings described in the literature (see Table 1 for a list of these studies). This database constitutes an important frame of reference from which to test the robustness of the properties and characteristics we derived for RecAR (as, for example, the presence of MWs at its core, or its subsurface nature since crossing the Walvis Ridge).

Table 1. List of all studies having described at least one Agulhas Ring in depth during ded-icated oceanographic cruises. It should be noted here that the list is limited to those AgulhasRings sufficiently documented in the referenced studies.

Article	Number of Eddy
Gordon et al. (1987)	2
M. S. McCartney and Woodgate-Jones (1991)	1
Duncombe Rae et al. (1992)	1
van Ballegooyen et al. (1994)	4
Duncombe Rae et al. (1996)	6
Arhan et al. (1999)	3
Garzoli et al. (1999)	3
McDonagh et al. (1999)	2
Schmid et al. (2003)	1
Gladyshev et al. (2008)	1
Arhan et al. (2011)	1
Casanova-Masjoan et al. (2017)	1
Guerra et al. (2018)	1
TOTAL	27

In the following section, we first introduce the general structure of the observed Agulhas Rings before focusing on MWs' properties, with an emphasis on those found within the rings. Finally, we compare estimates of their volume as well as heat and salt contents.

863

5.1 Agulhas Rings general vertical structure and classification

The Agulhas Ring described in this study is characterized by two cores of MW that concentrate the essential fraction of the eddy anomalies when compared to surrounding

waters. In this section, we wish to verify whether this is a common albeit not general 866 vertical water mass organization for Agulhas Rings. Out of the 27 referenced eddies, 23 867 were sufficiently described in the literature to be used for the comparison (Gordon et al., 868 1987: M. S. McCartney & Woodgate-Jones, 1991; Duncombe Rae et al., 1992; van Bal-869 legooyen et al., 1994; Duncombe Rae et al., 1996; Arhan et al., 1999; Garzoli et al., 1999; 870 McDonagh et al., 1999; Schmid et al., 2003; Gladyshev et al., 2008; Arhan et al., 2011; 871 Casanova-Masjoan et al., 2017; Guerra et al., 2018). We identified as single- or double-872 core MW eddies those Agulhas Rings whose vertical structure displayed one or two ho-873 mogeneous layers thicker than 100 m and separated by at least two isotherms of $\theta < 1^{\circ}C$ 874 and two isohalines of $PSU < 2^{\circ}$. Each of these eddies were observed during synoptic cruises. 875 Thus they can be associated with a single center position whereas the Agulhas Ring we 876 analyze in this study has been sampled by various Argo profiles along a segment of its 877 trajectory. Hence, it cannot be associated with a single position for its center. Conse-878 quently, hereinafter we use the averaged location of the segment of trajectory that we 879 reconstructed as the position of RecAR. 880

Of the 24 Agulhas Rings analyzed (i.e. 23 from the literature and our own RecAR), all show at least one core of water with homogeneous hydrological properties, and four exhibit two such cores (see Figure 15a). Three of them were observed northwest of the Cape Basin, as was the case for RecAR, whereas the other was found inside this basin.

We also tried to distinguish, among the documented rings in the literature, those 885 eddies that could be considered surface intensified and those (if any) that could be de-886 scribed as subsurface structures. The classification of eddies as surface or subsurface in-887 tensified structures is difficult from sparse CTD data. Indeed, due to air-sea interactions, 888 a seasonal thermocline can appear near the ocean surface that might not, necessarily, 889 isolate the eddy structure from the mixing layer during the entire annual cycle. Conse-890 quently, we have characterized eddies as subsurface intensified according to their shape. 891 Following the schematic view presented by Assassi et al. (2016), subsurface intensified 892 Agulhas Rings are defined as those anticyclones showing a lenticular shape with isopy-893 cnals on the top of the homogeneous core that are shallower at the eddy center and deeper 894 at the eddy edge. Among such categorization of subsurface eddies, an exception is the 805 eddy described in Guerra et al. (2018) whose structure was derived from a single pro-896 file. The first homogeneous core documented by Guerra et al. (2018) lies below 100 m. 897

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Figure 15. Number of a) cores and b) type of internal structure of the Agulhas Rings described in the literature. Each article is associated with a unique marker type. The gray shading patches in a) represent water depth shallower than 3500 m in the ETOPO2 dataset (Smith & Sandwell, 1997).

We associated it with a subsurface eddy, even if the horizontal structure of the eddy was not provided.

Of the 23 Agulhas Rings we selected from the literature, 10 of them (i.e. $~\tilde{}40~\%$ are 900 subsurface intensified and are indicated with red markers in Figure 15b. In general, they 901 align along the southeast-northwest diagonal in the center of the Cape Basin following 902 the main Agulhas Rings route (Dencausse et al., 2010; Guerra et al., 2018; Laxenaire et 903 al., 2018, e.g.) whereas the surface intensified ones (in blue in Figure 15b) lie closer to 904 the Agulhas Retroflection area and the continental slope of the Cape Basin. It is worth 905 noting that the eddy observed by Arhan et al. (2011) while it was sitting above the Ag-906 ulhas Ridge is also a surface intensified eddy associated with a surface mixed layer depth 907 of ~30 m which capped a homogeneous layer of more than ~500 m of thickness (Arhan 908 et al., 2011). Consequently, Arhan et al. (2011)'s characterization of this eddy as sur-909 face or subsurface is not straightforward. Similarly, the eddy described by Casanova-Masjoan 910 et al. (2017) shows a lenticular shape in salinity but not in temperature nor in poten-911 tial density (see Figure 3 in Casanova-Masjoan et al. (2017)). Consequently, its classi-912 fication as either a surface or subsurface eddy was also difficult. As its upper part lies 913

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very close to the ocean surface we categorized it as a surface intensified eddy. Three of
the subsurface intensified eddies showed a double core with homogeneous properties and
with a very similar vertical structure to RecAR. Like RecAR, two of them were found
in the Southeast Atlantic.

In conclusion, we categorized the whole set of Agulhas Rings in four different categories according to the number of cores with homogeneous properties and whether they were surface intensified eddies or not.

921

5.2 Agulhas Rings Mode Waters

The two-dimensional axisymmetric structure of RecAR has two distinct cores with 922 homogeneous water properties that fall into the MWs category. As these waters are re-923 sponsible for the majority of the eddy heat and salt anomalies (with reference to the en-924 vironmental waters), it is important to compare the RecAR properties with similar struc-925 tures documented in the literature in order to estimate the commonalities of their prop-926 erties as well as their origins. Of the 27 Agulhas Rings identified in previous studies (see 927 Table 1) that show one or two cores of MW, 5 (i.e. ~20 %) have their upper limit shal-928 lower than 50 m. For these five eddies, the subsurface homogeneous layer has been de-929 scribed by the authors of the relevant studies as a deep mixed layer. Deep homogeneous 930 layers are indeed thought to be the first and necessary phase of MW formation (e.g., Al-931 fultis & Cornillon, 2001; Joyce, 2012; Sato & Polito, 2014). These deep mixed layers have 932 been shown to be common in eddies, and they appear to occur more in anticyclones than 933 in cyclones (Kouketsu et al., 2012; Sato & Polito, 2014). 934

The hydrological properties of the documented Agulhas Ring MW cores are presented in Tables G1 and G2 in the Appendix. The position at which these eddies were sampled and their θ -S characteristics are shown, respectively, in panels a and b of Figure 16. Figure 16b shows that their properties range from 25.4 to 26.8 kg m⁻³ in σ_0 , from 12 to 19°C in potential temperature, and from 35.08 and 35.75 in (practical) salinity units.

As discussed in the Introduction, various MWs are described in the literature. We have summarized their properties in Table F1 in the Appendix. Even if very similar, they all show small property differences. Recently, de Souza et al. (2018) discussed a possible contribution of distinct MWs to South Atlantic Central Water (SACW). However,

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Figure 16. a) Position and b) hydrological properties in the mode water cores of the Agulhas Rings described in the literature. Each study discussing one or more of these eddies is associated with a specific marker and the color corresponds to a particular type of eddy. Double-core mode water eddies have two similar markers. The gray shaded patches in a) represent water depth shallower than 3500 m in the ETOPO2 dataset (Smith & Sandwell, 1997). The background lines in b) represent isopycnals of potential density anomalies referenced to the surface pressure (σ_0). The blue and green shaded patches highlight the hydrological properties of, respectively, SASTMW2 and SASTMW3 as described by Sato and Polito (2014).

as they decomposed SACW by MW contribution, the specific hydrological properties of
the various SATMWs cannot be derived directly from that publication.

Here, we compared the whole set of Agulhas Ring MWs (that includes RecAR and all those found in the literature) to Sato and Polito (2014) SATMWs. Figure 16 presents the Sato and Polito (2014) SATMWs' hydrological distributions as areas shaded in blue (SASTMW2) and green (SASTMW3). We do not consider here SASTMW1, which is only found west of 30°W whereas SASTMW2 and SASTMW3 occupy the eastern South Atlantic sector. SASTMW2 and SASTMW3 are separated by the 35°S parallel (see Figure 4 in Sato and Polito (2014)).

Agulhas Ring MW core properties fall in the range of SASTMW2 and SASTMW3. 953 Moreover, more than 50% of these Agulhas Ring MW cores have properties within the 954 generic SASTMW characteristics (see Table F1 in the Appendix). In particular, nearly 955 all the surface Agulhas Rings that have a single MW core (in black) are in the range of 956 SASTMW2, whereas the whole set of subsurface Agulhas Rings with a simple MW core 957 (green) fall in the SASTMW1 category. The only exception is the eddy described by Arhan 958 et al. (2011), which shows a particularly thick homogeneous layer capped by a narrow 959 surface layer. We identified it as a surface intensified eddy as the surface layer was only 960 30 m thick. However, this eddy, observed by the 2008 GoodHope cruise in late Febru-961 ary, was clearly at the beginning of a phase described as a subduction by Arhan et al. 962 (2011) as the eddy disappeared from the altimetry a few months later (at the beginning 963 of April 2008, (Arhan et al., 2011)). Given the size and energy of this Agulhas Ring, it 964 is improbable that it simply dissipated so quickly. 965

If we look at the spatial organization of single MW core Agulhas Rings in Figure 16a, we see that those that are surface intensified mainly lie near the African continental slope covering the eastern part of the Cape Basin. The subsurface ones, on the other hand, are essentially found in the central part of the basin, along the Agulhas Ring central path (Laxenaire et al., 2018).

Double-core MW Agulhas Rings have a simpler distribution. Most (4) subsurface double-core MW rings were observed north/north-west of the Cape Basin. That described by M. S. McCartney and Woodgate-Jones (1991) shows SASTMW2 characteristics, whereas the others three (Garzoli et al. (1999), Guerra et al. (2018) and RecAR) have properties falling in both varieties of SASTMW (see Figure 16b). Only one surface double-core

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eddy was identified in the literature so far (by Casanova-Masjoan et al. (2017)) lying in
the center of the Cape Basin. The MW cores of this show both, SASTMW2 and SASTMW3
properties.

Arhan et al. (1999) and Arhan et al. (2011) have suggested that Agulhas Ring hy-979 drological properties are intimately linked to their history. Indeed, these studies have 980 suggested that the route undertaken by these eddies (northern, central or southern ac-981 cording to Dencausse et al. (2010)), the time they spend within the subantarctic regions, 982 and whether they experience a wintering or not are all factors that determine the wa-983 ter properties of the upper 1000 m of these structures, mediated by strong air-sea inter-984 actions and mixing with environmental water. This might explain why, even if some cor-985 respondence between geographical regions and Agulhas Ring characteristics appear, there 986 seems not to be a clear pattern. On the other hand, Garzoli et al. (1999) and Gladyshev 987 et al. (2008) have suggested that Agulhas Rings displaying a multiple core structure might 988 be explained either by the merging of two rings with distinct histories or by two consec-989 utive mode water formations during consecutive years. 990

Our study cannot completely explain the origins and diversity of Agulhas Ring MW 991 properties and structure. Indeed, while the formation of the upper MW core was well 992 captured by the profiles achieved by Argo float No. 5902281 during the time it was trapped 993 within the eddy core, we do not have any information on the MW ventilation of the sec-994 ond and deeper one. The whole set of profiles that sampled Segments 1, 2, and 3 before 995 they merged into Segments 4 and 5 (see Figure 2) did not sample the eddy structures 996 close to the center so they cannot be assumed to characterize the inner eddy vertical struc-997 ture. It should be noted that Segment 1 spent an entire winter south of 40° S, in the strong 998 westerlies blowing in the subantarctic region, before merging with Segment 4 to form Seg-999 ment 5. Segment 1 is very close, albeit it crossed the Walvis Ridge slightly north of the 1000 eddy observed by Arhan et al. (2011). This could explain the fact that both eddies dis-1001 play SASTMW2 characteristics, but that the deeper core of RecAR is relatively warmer 1002 and saltier than the homogeneous layer of the eddy discussed by Arhan et al. (2011), sug-1003 gesting that RecAR underwent less intense air-sea interactions. Other published stud-1004 ies have suggested that MWs observed within Agulhas Rings are or might derive from 1005 modified (Indian) SAMW (e.g., Arhan et al., 1999; Gladyshev et al., 2008) or Subtrop-1006 ical Indian MW (de Souza et al., 2018). However, the definitions of these two MWs are 1007 not precise (see Table F1 in the Appendix) and this prevents any clear conclusion. We 1008

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can merely suggest that Agulhas Rings are large coherent structures advecting, south 1009 of Africa, Agulhas Current waters (i.e., Subtropical Indian waters). These waters are trans-1010 formed along the way by ocean-atmosphere interactions. As suggested by Arhan et al. 1011 (2011), these exchanges, when occurring during winter, give rise to episodes of intense 1012 convection that are accompanied by lateral mixing with environmental water. Indeed, 1013 the large cooling and freshening of the homogeneous layer waters can be explained only 1014 by taking into account both processes. Moreover, the more intense the convection, the 1015 larger the mixing and therefore the greater the cooling and freshening. This can eluci-1016 date why the eddy observed by Arhan et al. (2011) southward of Segment 1's actual tra-1017 jectory showed lower temperature and salinity than RecAR. 1018

The precise processes involved in the formation of relatively deep mixed layers within 1019 Agulhas Rings and how these layers transform into MW cores have not been directly ob-1020 served. However, by using very high-resolution numerical simulations, Capuano et al. 1021 (2018) showed that submesoscale instabilities (of different type) are responsible for both 1022 deep mixing layer formation during winter and the upper-layer restratification during 1023 summer as discussed in Section 3.2 describing possible mechanisms of subduction. More-1024 over, this type of instability leads to mixing layer water subduction and the formation 1025 of a local variety of mode water that the authors defined as Agulhas Ring Mode Water 1026 (ARMW) and whose properties depend on the eddy history. These numerical results, 1027 as well as our analyses on the observed Agulhas Ring MW properties, would suggest that 1028 MWs found in Agulhas Ring cores are formed within these eddies and not a regional va-1029 riety of SASTMW corresponding to a more classical and larger-scale definition of wa-1030 ter mass subduction. Yet, from the *in situ* data we have analyzed we are not able to re-1031 construct the entire evolution of RecAR, neither are we able to demonstrate unequiv-1032 ocally that ARMWs are the same water masses as SASTMW2 and SASTMW3, nor that 1033 they can be found only within eddies. 1034

1035

5.3 Agulhas Rings volume transport, and heat and salt contents

Table 2 presents the estimates of the volume as well heat and salt content anomalies for 17 of the 27 Agulhas Rings found in the literature for which at least one of these values was provided by the authors of the studies in question. When the authors give more than one value for these variables for one eddy, we only provide those estimates computed using the closest boundaries of integration to ours. The average Agulhas Ring volume, HCA, and SCA in the literature are, respectively, $3.4 \times 10^{13} \pm 1.6 \times 10^{13} \text{ m}^{-3}$, $1.0 \times 10^{20} \pm 0.7 \times 10^{20} \text{ J}$, and $5.2 \times 10^{12} \pm 3.6 \ 10^{12} \text{ kg}$. Hence RecAR proves to be one of the strongest and largest Agulhas Rings ever observed. The estimated volume and HCA are more than double that of the Agulhas Ring documented values, and the SCA is slightly higher than their average.

All rings, with the exception of RecAR and two others (M. S. McCartney & Woodgate-1046 Jones, 1991; Garzoli et al., 1999), were found in the Cape Basin. It might therefore be 1047 possible that the large values of RecAR for both HCA and SCA are due to a lateral mix-1048 ing with surrounding waters. However, the fact that the waters trapped within the eddy 1049 show different properties from the environment and the MW cores are similar to those 1050 found in other Agulhas Rings gives us confidence that RecAR is a coherent mesoscale 1051 eddy advecting modified Indian waters into the South Atlantic. Beyond these conjec-1052 tures, we can compare assessments of these integrated properties for RecAR and the rings 1053 documented in the literature by using the same approach as in the related articles. The 1054 results are presented in Table H1 in the Appendix where the values given in the articles 1055 are expressed as a percentage of the values for the same variables obtained for RecAR. 1056 This comparison shows that, even if we do not consider the upper 200 m of the water 1057 column for RecAR, it still results in the largest volume. RecAR is also one of the rings 1058 with the highest hydrological anomalies, higher than all but 2 and 4 of the other 16 for, 1059 respectively, RecAR HCA and SCA. However, these rings were observed close to the Ag-1060 ulhas Retroflection area. 1061

1062

6 Summary and conclusions

We have analyzed the evolution of a long-lived Agulhas Ring during 1.5 years of 1063 its lifespan by simultaneously using a new eddy-tracking algorithm (TOEddies) applied 1064 to satellite altimetry maps and Argo floats to uncover the eddy's hydrological proper-1065 ties. This eddy was sampled by a large number of Argo profiles (71) between the north-1066 ern region of the Cape Basin and the Mid-Atlantic Ridge, similarly to the eddies discussed 1067 by J. M. A. C. Souza et al. (2011) and Nencioli et al. (2018). In particular, one of the 1068 Argo floats (No. 5902281) remained trapped within the eddy core for 14 months (from 1069 October 2012 to November 2013), which provided a vertical snapshot of the eddy every 1070 10 days. We also selected all additional Argo profiles lying at less than 200 km from the 1071 eddy center. However, we made a careful distinction between the profiles sampling the 1072

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Table 2. Integrated properties of Agulhas Rings described in the literature. The reference for the bottom limit of integration is given in the last column. The integrations are achieved either from an isotherm for a fixed depth or by identifying the coherent part of the eddy assessed, following Flierl (1981), as the volume of the eddy where eddy velocities are lower than the eddy drifting speed. The upper limit of integration is the surface for all eddies except RecAR, for which the integration is limited to $\sigma_0=26.2$ kg m⁻³.

Article	Eddy	Volume [m ³]	HCA [J]	SCA[kg]	Reference
McCartney & Woodgate-Jones, (1991)	Eddy	3.6×10^{13}			Trap $5 \times 10^{-2} \text{ m s}^{-1}$
van Ballegooyen et al., (1994)	A3	4.31×10^{13}	1.5×10^{20}	8.74×10^{12}	T > 8° C
van Ballegooyen et al., (1994)	A4	$3.94 \ 10^{13}$	2.36×10^{20}	$ 13.1 \times 10^{12}$	$T > 8^{\circ} C$
van Ballegooyen et al., (1994)	A5	1.53×10^{13}	0.73×10^{20}	4.35×10^{12}	T > 8° C
van Ballegooyen et al., (1994)	A6	2.45×10^{13}	1.06×10^{20}	4.59×10^{12}	T > 8° C
Duncombe Rae et al., (1996)	B1-1		0.19×10^{20}	1.21×10^{12}	800 m
Duncombe Rae et al., (1996)	B2-1		0.24×10^{20}	1.52×10^{12}	800 m
Duncombe Rae et al., (1996)	B2-2		0.57×10^{20}	3.8×10^{12}	800 m
Duncombe Rae et al., (1996)	B2-3		0.55×10^{20}	3.72×10^{12}	800 m
Duncombe Rae et al., (1996)	B2-4		0.42×10^{20}	1.67×10^{12}	800 m
Duncombe Rae et al., (1996)	B3-1		0.6×10^{20}	3.88×10^{12}	800 m
McDonagh et al, (1999)	R1	1.5×10^{13}	0.39×10^{20}	2.43×10^{12}	T > 10° C
McDonagh et al, (1999)	R2	4.7×10^{13}	0.44×10^{20}	2.71×10^{12}	T > 10° C
Garzoli et al., (1999)	R-1	2.8×10^{13}	1.33×10^{20}	8×10^{12}	1100 m
Garzoli et al., (1999)	R-2	4.18×10^{13}	1.31×10^{20}		1100 m
Garzoli et al., (1999)	R-3	1.88×10^{13}	0.77×10^{20}		1100 m
Schmid et al., (2003)	JAR	2.8×10^{13}	1.71×10^{20}	10.7×10^{12}	1100 m
This study	RecAR	7.1×10^{13}	2.5×10^{20}	6.8×10^{12}	Trap $6 \times 10^{-2} \mathrm{~m~s^{-1}}$

eddy within its boundaries and those characterizing the environment. This was possible as the TOEddies method automatically computes, for every detected eddy, its outer
and characteristic contours together with the evolution of its surface properties.

The eddy we discussed in this study corresponds to a segment of an Agulhas Ring 1076 main trajectory (according to the definition of Laxenaire et al. (2018)) that has been tracked 1077 by TOEddies for 4 years and 7 months (from January 2011 to July 2015). This segment 1078 was generated in the Cape Basin by the merging of three different Agulhas Rings. Along 1079 this segment the eddy proved to be particularly coherent in its shape whereas its sur-1080 face ADT anomaly, velocity, and —Ro— decreased with time, as previously observed 1081 for other rings (e.g., Byrne et al., 1995; Schouten et al., 2000; Guerra et al., 2018; Lax-1082 enaire et al., 2018). 1083

The subsurface observations of the eddy were characterized by two distinct peri-1084 ods: one in austral winter, during which the mixing layer in the eddy deepened signif-1085 icantly, and a second in austral summer, during which the upper hydrological core of the 1086 eddy subsided while propagating west. We showed that the eddy, when capped by sur-1087 face warmer layers, is characterized by negative SST anomalies that support, according 1088 to Assassi et al. (2016), its characterization as a subsurface intensified eddy. This study 1089 represents, to our knowledge, the first Lagrangian evidence of the subduction of an Ag-1090 ulhas Ring. This result is supported by previous observations of a subducted Agulhas 1091 Ring (Arhan et al., 1999) and numerical studies by Herbette et al. (2004). However, from 1092 the data we have analyzed, we cannot infer precisely the mechanism that acted to sep-1093 arate the coherent part of the eddy from the upper layers. Indeed, we document the pres-1094 ence of significantly different water masses in the Agulhas Ring compared with the en-1095 vironment. The upper-layer hydrological properties of the Agulhas Ring appear differ-1096 ent from the environment, too, but they are also distinct from those of the eddy core be-1097 low. This indicates a clear separation of the Agulhas Ring core from the surface, result-1098 ing in a less coherent upper-layer behavior that enables the Agulhas Ring and surround-1099 ing waters to mix (e.g., Wang et al., 2015), producing modified water of Indian-Atlantic 1100 origins. Hence, for the particular Agulhas Ring discussed in this study, it appears that 1101 the eddy still influences the velocity in the surface waters rather than being completely 1102 separated. 1103

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The transition from a surface to a subsurface intensified eddy concomitant with the 1104 trapping of a profiling float is of a great interest in light of the question about the abil-1105 ity of eddy detection methods to detect coherent eddies (e.g., Abernathey & Haller, 2018) 1106 from a surface field. In the same way as in previous studies (J. M. A. C. Souza et al., 1107 2011; Nencioli et al., 2018), the TOEddies eulerian detection algorithm showed it could 1108 successfully identify and track a coherent eddy as it is able to trap a profiling float for 1109 more than one year. However, the observation of the subduction of the eddy enabled us 1110 to go beyond these results as it documented that a reduction in the eddy surface inten-1111 1112 sity is not associated with the global dissipation of the structure, but with its subsidence in the ocean interior. Indeed, the subducted eddy conserves its size and properties, and 1113 the maximum geostrophic velocity seems to move, while subducting, from the ocean sur-1114 face to a depth of 200 m. In this case, the velocities at the surface still satisfy the trap-1115 ping water conditions of Flierl (1981) and Chelton et al. (2011). However, we might ex-1116 pect this to not always be the case for the water column encompassing the surface layer 1117 and the full structure of the eddy at depth. This would result in an incoherent eddy-like 1118 behavior in the surface layer while the deeper layers of the eddy continued to behave as 1119 a coherent structure. Moreover, as the surface geostrophic velocity decreases, we can ex-1120 pect the signal-over-noise ratio to increase in satellite altimetry maps. This ratio is par-1121 ticularly important for Lagrangian eddy detection techniques (e.g., Beron-Vera et al., 1122 2013; Abernathey & Haller, 2018) and it is very sensitive to absolute values of the sur-1123 face velocities. Therefore we advise caution when analyzing eddies' coherence from sur-1124 face fields only and, in particular, when estimating the Agulhas Leakage achieved by Ag-1125 ulhas Ring (e.g., Wang et al., 2015, 2016). Indeed, our results suggest that Agulhas Ring 1126 can behave as a coherent structure, but mainly so within the subsurface layers. 1127

Another possible consequence of the subduction process might be the formation of mode water layer cores. Indeed, the eddy we studied presented two cores of mode waters. One of these was very likely linked to the last winter convection as described by Capuano et al. (2018). A second one, located deeper, was probably linked to a merging of an Agulhas Ring that took, after being spawned by the Agulhas Retroflection, the Southern Route defined by Dencausse et al. (2010) and experienced more intense winter conditions.

Given the long-lasting coherence of the structure after subduction, which shielded the eddy from any further air-sea exchanges, we assumed it was steady and axisymmet-

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ric. This allowed us to reconstruct its three-dimensional hydrological vertical structure 1137 by fitting an alpha Gaussian function (e.g., Carton, 2001; Le Vu et al., 2018; Zeitlin, 2018). 1138 We defined the eddy thermohaline anomalies in relation to the surrounding environment. 1139 These anomalies turned out to be very intense and concentrated within the two mode 1140 water layers, and they concentrated the majority of the anomaly signal distinguishing 1141 this eddy from the surrounding South Atlantic waters. Our reconstruction is similar to 1142 the approach of Nencioli et al. (2018) who studied a different eddy. However, it differs 1143 in the choice of the variables of integration and in the definition of the eddy boundaries. 1144 Indeed, we carefully considered only profiles falling strictly within the eddy limits (lat-1145 eral and vertical) with a view to accurately representing the eddy thermohaline struc-1146 ture. 1147

A comparison with 27 other Agulhas Ringdescribed in the literature from oceano-1148 graphic cruises shows that we can subdivide them into surface and subsurface intensi-1149 fied rings. The surface intensified rings mainly lie in the Cape Basin, along the South-1150 ern Africa slope. Those located along the main ring path that occupies the central part 1151 of the Cape Basin (Laxenaire et al., 2018) are predominantly subsurface intensified ed-1152 dies. Moreover, the rings for which we have found in the literature a vertical section of 1153 their thermohaline properties are all characterized by the presence of at least one core 1154 of mode waters. Some of them show two mode water cores (including the eddy we fo-1155 cus on in this study). For these, all but one are located in the South Atlantic, north of 1156 the Cape Basin. Hence, the results of the comparison suggest that the subsurface eddy 1157 we reconstructed in this work, which is composed of two homogeneous cores, is not an 1158 exception. Moreover, this analysis provides indications that Agulhas Rings follow a ge-1159 ographical pattern according to their history and water mass properties. Such a distri-1160 bution needs to be investigated further from updated data, complementary modeling stud-1161 ies, and by applying reproducible quantitative methods. 1162

The mode waters found in Agulhas Rings show very variable properties that fall within the range of two varieties of SASTMW (Sato & Polito, 2014) and in the upper (warmer and saltier) range of SAMW (M. S. McCartney & Woodgate-Jones, 1991). However, the continuity of their θ -S properties would rather suggest that these eddies are associated with one specific variety of mode water formed within Agulhas Rings during the austral winter (the so-called ARMW as suggested from modeling studies by Capuano et al. (2018)) and not to different types of mode waters formed remotely. Indeed, south

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of Africa the ocean is submitted to intense wind forcing and buoyancy exchanges that 1170 affect in particular the warm and salty Agulhas Current and Agulhas Rings (e.g., van 1171 Ballegooyen et al., 1994; Arhan et al., 1999, 2011). The assorted properties observed for 1172 ARMWs might be due to the different amplitude of such air-sea fluxes as these vary ac-1173 cording to the path undertaken by the rings, as well to the synopticity of the atmospheric 1174 forcing that can vary from one week to another as well as one year from the following, 1175 or according to the time the rings spend in the area as they can be blocked for several 1176 months by the interaction with the local topography (e.g., Arhan et al., 1999, 2011). Yet 1177 our study cannot assess whether the formation of the observed mode waters are restricted 1178 to Agulhas Rings only, nor can it define the origin of the observed mode waters for the 1179 double-core rings. The latter might indeed be the result of convection within an eddy 1180 during two consecutive winters or of the merging of two rings that took different routes 1181 and underwent different weather conditions (Garzoli et al., 1999). Also, the deeper mode 1182 water core could be a remnant of SAMW advected within the Agulhas Current from the 1183 Indian Ocean and already present in the eddy at the moment it was spawned from that 1184 current. 1185

We calculated the geostrophic velocity of the reconstructed eddy from the nonlin-1186 ear thermal wind relation. The maximal value of the azimuthal velocity (0.3 m s^{-1}) was 1187 found at 200 m and had the same radius as the speed radius derived from satellite al-1188 timetry. The surface maximum azimuthal velocity was more intense (up to 0.35 m s^{-1}) 1189 than its subsurface expression from Nov 2012 to January 2013. After this period it de-1190 creased steadily to reach 0.15 m s^{-1} at the end of the Argo float No. 5902281 observ-1191 ing period. This is a consequence of the eddy subduction that implies at least a partial 1192 disconnection of the eddy from the ocean surface. Our analysis suggests that the eddy 1193 extended, after subduction, from a depth of 200-1200 m. We estimated its volume at $7.1 \times 10^{13} \pm$ 1194 1.5×10^{13} m⁻³. The heat and salt anomalies transported by the eddy amounted to, re-1195 spectively, 4 $^{\circ}$ C and 0.6 g kg⁻¹ at a depth of 600 m and the total integrated Heat Con-1196 tent Anomalies (HCA) and Salt Content Anomalies (SCA) were estimated at $2.5 \times 10^{20} \pm$ 1197 0.1×10^{20} J and $6.8 \times 10^{12} \pm 0.1 \times 10^{12}$ kg, respectively. Both the volume and the hydro-1198 logical anomalies proved to be particularly large when compared with comparable es-1199 timates for Agulhas Rings found in the literature. Only Agulhas Rings close to the Ag-1200 ulhas Retroflection show comparably large integrated hydrological anomalies (e.g., van 1201 Ballegooyen et al., 1994; Arhan et al., 1999, 2011; Schmid et al., 2003). 1202



Figure A1. Trajectories and names of the profiling floats that sampled the AREN of interest. The profiles used in this study are marked by crosses.

Our analysis sheds light on the complex evolution of Agulhas Rings that split and 1203 merge, undergo intense ventilation, and subduct but remain intense while crossing the 1204 South Atlantic basin. They advect very large quantities of water, heat, and salt from the 1205 Indian Ocean. South of Africa, Agulhas Ring waters are (at least partially) modified by 1206 winter convection that produces thick cores of mode waters. It is in these mode water 1207 cores that the strongest heat anomaly of these intense eddies seems to reside, when they 1208 are advected in the South Atlantic Ocean. This, together with the numerous eddy merg-1209 ing and splitting occurrences, strongly suggests that the use of exclusively satellite al-1210 timetry maps to characterize the coherence of eddies has limitations and that coupling 1211 with Argo profiles is very useful. 1212



Figure B1. Bathymetry below the fifth trajectory segment of the Agulhas Ring main trajectory studied in this work from the ETOPO2 dataset (Smith & Sandwell, 1997).



Figure C1. Monthly averaged SST anomalies in the moving reference frame of the 5th segment of the AREN interpolated from the ODYSSEA SST dataset (Dash et al., 2012; Martin et al., 2012). These anomalies are computed by subtracting the mean SST in each panel from the -56-SST values at each point.



Figure D1. CT-S diagram of Argo profiles with a Dc < 25 km in red and those with a 150 < Dc < 200 km in blue sampling segment 5 between November 2012 and November 2013.



Figure E1. σ_0 anomalies derived from Argo observations (circles) and from the reconstructed Agulhas Ring (solid black lines) at 6 different depths as a function of the distance from the eddy center (Dc). The date for each observation is indicated by the color of the circles.

Table F1. Hydrological properties Potential Temperature (θ in °C), Practical Salinity (S in PSU) and Potential Density (σ_{θ} in kg m⁻³) of mode waters found in the South Atlantic as described in the literature. The standard deviations (STD) is provided using the \pm symbol when it is explicitly supplied in the articles.

Acronym	Full Name	θ [°C]	PSU [psu]	$\sigma_{\theta} \; [\mathrm{kg \; m^{-3}}]$	Reference
SAMW	Subantarctic MW	4-15	34.2-35.8	26.5-27.1	McCartney [1977,1982]
SASTMW	South Atlantic STMW	12-18	35.2-36.2	26.2-26.6	Provost et al. [1999]
SAESTMW	South Atlantic Eastern STMW	15-16	35.4	26.2-26.3	Provost et al. [1999]
SASTMW1	South Atlantic STMW 1	$ 15.0 \pm 0.9$	35.6 ± 0.2	26.4 ± 0.1	Sato & Polito [2014]
SASTMW2	South Atlantic STMW 2	$ 16.7 \pm 0.9$	35.7 ± 0.2	26.1 ± 0.1	Sato & Polito [2014]
SASTMW3	South Atlantic STMW 3	$ 13.2 \pm 0.9$	35.2 ± 0.2	26.5 ± 0.1	Sato & Polito [2014]
STMW ₁₈	STMW $\theta = 18$	18 ± 0.56	35.8 ± 0.11	25.9	de Souza et al. [2018]
STMW ₁₄	STMW $\theta = 14$	14 ± 0.53	35.40 ± 0.01	26.5	de Souza et al. [2018]
STMW ₁₂	STMW $\theta = 12$	12 ± 0.50	35.03 ± 0.14	26.6	de Souza et al. [2018]
SIMW	Subtropical Indian MW	17 ± 0.28	35.57 ± 0.54	26.0	de Souza et al. [2018]

Table G1. Properties of the Agulhas Ring cores described in the literature. The precision ofthe variables is not fixed as it depends on each article.

Article	Eddy.Core Number	Depth [m]	Thickness [m]	θ [° C]	PSU []
Gordon et al., 1987	CTE.1	-230	200	16	35.5
McCartney and Woodgate-Jones, 1991	Eddy.1	-150	100	17.5	35.75
McCartney and Woodgate-Jones, 1991	Eddy.2	-250	100	15.5	35.45
Duncombe Rae et al., 1992	Ring.1	-50	100	19	35.66
van Ballegooyen et al., 1994	A4.1	-70	140	18.83	35.71
Duncombe Rae et al., 1996	B1-1.1	-150	300	16.65	35.49
Duncombe Rae et al., 1996	B2-1.1	-300	400	13.13	35.24
Duncombe Rae et al., 1996	B2-2.1	-100	200	15.84	35.58
Duncombe Rae et al., 1996	B2-3.1	-50	100	18.33	35.72
Duncombe Rae et al., 1996	B2-4.1	-100	200	18.96	35.57
Duncombe Rae et al., 1996	B3-1.1	-300	400	13.73	35.37
Arhan et al., 1999	R1.1	-325	350	11.6	35.08
Arhan et al., 1999	R2.1	-150	120	17.1	35.71
Arhan et al., 1999	R3.1	-350	300	13.6	35.34
McDonagh et al, 1999	R1.1	-325	450	13	35.2
McDonagh et al, 1999	R2.1	-150	100	18	35.5

Article	Eddy.Core Number	Depth [m]	Thickness [m]	Pt0 [° C]	PSU []
Garzoli et al., 1999	R-1.1	-100	200	16.13	35.59
Garzoli et al., 1999	R-2.1	-510	140	12.13	35.1
Garzoli et al., 1999	R-3.1	-270	100	15.22	35.51
Garzoli et al., 1999	R-3.2	-350	150	14.39	35.35
Schmid et al., 2003	JAR.1	-50	100	19	35.6
Gladyshev et al., 2008	E3.1	-400	500	12.5	35.2
Arhan et al., 2011	Eddy M.1	-380	550	11.8	35.15
Casanova-Masjoan et al., 2017	ACR.1	-145	170	16.6	35.6
Casanova-Masjoan et al., 2017	ACR.2	-400	100	13.4	35.34
Guerra et al., 2018	Lilian.1	-200	160	16.5	35.65
Guerra et al., 2018	Lilian.2	-480	240	12.5	35.2
This study	AR.1	-290	180	16.1	35.7
This study	AR.2	-560	100	12.9	35.3

Table G2. Properties of the Agulhas Ring cores described in the literature. The precision ofthe variables is not fixed as it depends on each article.

Table H1. Integrated properties of the Agulhas Rings described in the literature expressed as percentage of the same variables obtained for RecAR using the same parameter to compute the maximum depth of integration. We do not compare volume for a fixed depth as this is not relevant here.

Article	Eddy	Volume	HCA	SCA	Reference
McCartney & Woodgate-Jones, (1991)	Eddy	46%			Trap $5 \times 10^{-2} \text{ m s}^{-1}$
van Ballegooyen et al., (1994)	A3	72%	71%	123%	$T > 8^{\circ} C$
van Ballegooyen et al., (1994)	A4	66%	112%	186%	$T > 8^{\circ} C$
van Ballegooyen et al., (1994)	A5	26%	35%	61%	$T > 8^{\circ} C$
van Ballegooyen et al., (1994)	A6	41%	50%	65%	$T > 8^{\circ} C$
Duncombe Rae et al., (1996)	B1-1		8%	16%	800 m
Duncombe Rae et al., (1996)	B2-1		10%	21%	800 m
Duncombe Rae et al., (1996)	B2-2		24%	51%	800 m
Duncombe Rae et al., (1996)	B2-3		23%	50%	800 m
Duncombe Rae et al., (1996)	B2-4		18%	22%	800 m
Duncombe Rae et al., (1996)	B3-1		25%	52%	800 m
McDonagh et al, (1999)	R1	31%	23%	38%	$T > 10^{\circ} C$
McDonagh et al, (1999)	R2	96%	26%	42%	$T > 10^{\circ} C$
Garzoli et al., (1999)	R-1		78%	125%	1100 m
Garzoli et al., (1999)	R-2		77%		1100 m
Garzoli et al., (1999)	R-3		45%		1100 m
Schmid et al., (2003)	JAR		101%	167%	1100 m

Appendix A Argo profiling float trajectories 1213 Appendix B Bathymetry below the fifth trajectory segment 1214 Appendix C SST anomalies 1215 Appendix D CT-S diagram 1216 Appendix E Examples of potential anomalies reconstruction 1217 Appendix F Hydrological properties of Mode Waters found in the South 1218 Atlantic as described in the literature. 1219 Appendix G Hydrological properties of the Agulhas Ring's cores de-1220 scribed in the literature. 1221 Appendix H Integrated properties of the Agulhas Rings described in 1222 the literature. 1223

1224 Acknowledgments

The database produced for this paper and scripts to reproduce the main figures presented 1225 in the results are available at the following: https://vesg.ipsl.upmc.fr/thredds/catalog/ 1226 IPSLFS/datapapers/Laxenaire_Database_AR_Recont/catalog.html. The gridded satel-1227 lite altimetry data we used in this work were produced by SSALTO/DUACS and dis-1228 tributed by the Copernicus Marine Environment Monitoring Service. The Argo data were 1229 collected and made freely available by the International Argo Program and the national 1230 programs that contribute to it (http://coriolis.eu.org and http://www.argo.ucsd 1231 .edu). The Argo Program is part of the Global Ocean Observing System. The GHRSST 1232 Level 4 ODYSSEA Global Foundation Sea Surface Temperature Analysis product was 1233 created by IFREMER/CERSAT with the support of the European Commission GMES 1234 Framework. This work was supported by the European Union's Horizon 2020 research 1235 and innovation program under grant agreement no. 633211 (AtlantOS), a CNES-TOSCA 1236 research grant, and the 11-ANR-56-004 SAMOC research grant for SS and RL and the 1237 ANR-Astrid Project DYNED-Atlas (ANR-15-ASMA-0003-01) for AS and RL. The au-1238 thors received several helpful suggestions for improving an earlier version of this manuscript 1239 from A. Doglioli, I. Borrione and two anonymous reviewers, and their help is gratefully 1240 noted. We also acknowledge the mesoscale calculation server CICLAD (http://ciclad 1241 -web.ipsl.jussieu.fr) dedicated to Institut Pierre Simon Laplace modeling effort for 1242 technical and computational support. 1243

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