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Paleo Agulhas rings enter the subtropical gyre during the penultimate deglaciation

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Abstract

A maximum in the strength of Agulhas Leakage has been registered at the interface between Indian and South Atlantic oceans during glacial Termination II (T II), presumably transporting the salt and heat necessary to maintain the Atlantic Meridional Overturning Circulation (AMOC) at rates similar to the present day. However, it was never shown whether these were effectively incorporated in the South Atlantic gyre, or whether they retroflected into the Indian and/or Southern Oceans. To solve this question, we investigate the presence of paleo Agulhas rings from a sediment core on the central Walvis Ridge, almost 1800 km farther into the Atlantic basin than previously studied. Analysis of a 20 yr dataset from a global ocean circulation model allows us to relate density perturbations, at the depth of the thermocline, to the passage of individual rings over the core site. Using this relation from the numerical model as the basis for a proxy, we generate a time series of δ^{18}O variability of *Globorotalia truncatulinoides* single specimens, revealing high levels of pycnocline depth variability at the site, suggesting enhanced numbers of Agulhas rings moving into the South Atlantic gyre around and before T II. Our record closely follows the published quantifications of Agulhas Leakage from the east of the Cape Basin, and thus shows that Indian Ocean waters entered the South Atlantic circulation. This provides crucial support to the view of a prominent role of the Agulhas Leakage in the shift from a glacial to an interglacial mode of AMOC.

1 Introduction

A transport of upper water masses takes place around the tip of South Africa, where the Agulhas Current retroflection spills Indian Ocean waters into the South Atlantic (Lutjeharms, 2006; Beal et al., 2011, and references therein). This Agulhas Leakage (hereafter AL) is an important component of the salt and heat balance of the AMOC (Gordon et al., 1992; Weijer et al., 2001; Dong et al., 2012). The receiver of this transfer is the

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Cape Basin, in which a host of complex and turbulent phenomena occur (e.g. Olsen and Evans, 1986; Boebel et al., 2003; Doglioli et al., 2006).

Waters of Indian Ocean origin travel across the Cape Basin in a variety of forms and shapes. These can be broadly characterized as anticyclonic eddies (Agulhas rings "sensu stricto"), cyclonic eddies, and filaments (or streamers, or liners) wound between the spinning eddies (Lutjeharms and Cooper, 1996; Treguier et al., 2003). It is not yet clear how the AL is partitioned between these transport features (e.g. Doglioli et al., 2006; van Sebille et al., 2010a), but a significant part of the AL is in the form of rings (van Sebille et al., 2010a; Dencausse et al., 2010).

1.1 Agulhas rings and the thermocline

Agulhas rings have been described as quite regular features of mostly barotropic flow, and as the greatest and most energetic mesoscale eddies in the world (Clement and Gordon, 1995; Olson and Evans, 1986). Approximately six rings are spawned per year and they reach, though then very diminished, as far as 40° W (Byrne et al., 1995). Their most conspicuous characteristic, upon entrance in the Cape Basin, is the dramatic depression they impose on isotherms, isopycnals and isohales (Arhan et al., 2011; Souza et al., 2011; Giulivi and Gordon, 2006), as they transport water that is much warmer and more saline than the surroundings, from the sub-surface to at least ~ 1000 m depth (van Aken et al., 2003).

It is understood indeed that the bulk of the AL happens beyond the surface, at the depths of the thermocline (Donners and Drijfhout, 2004; Doglioli et al., 2006; Van Sebille et al., 2010b). Observations of Gordon et al. (1992) show that across the Cape Basin thermocline, two thirds of the water between the 9 °C and 14 °C isotherms is of Indian Ocean origin. The observational study of Richardson (2007) reveals that while surface drifters adopt more northerly trajectories, closer to the Benguela Current, floats at ~ 800 m travel right over the central Walvis Ridge. Souza et al. (2011) maintain that the largest heat perturbation introduced by Agulhas rings occurs at depths comprised between 200 and 600 m.

1.2 In search for a missing paleo link

In the last decades, researchers have come to consider the AL mechanism to play an important role in the modes of AMOC circulation during Pleistocene climate shifts (e.g. Berger and Wefer, 1996). The hypothesis of reduced Indian to Atlantic transfer during glacial periods is compatible with the northward shift of the oceanographic fronts south of Africa (Hays et al., 1976; Bé and Duplessy, 1976; Bard and Rickaby, 2009).

While paleoceanographic research on marine sediment has made a convincing case that Agulhas Current (Hutson, 1980), and AL (Franzese et al., 2006) were reduced during glacial times, most of that evidence was gathered in the easternmost part of the Cape Basin, depicting intense presence of Indian Ocean waters during glacial terminations (Flores et al., 1999; Peeters et al., 2004) (Fig. 1). As modern observations show, Agulhas rings that reach such regions often bend south, to reach the Southern Ocean, or join the Agulhas retroflection (Dencausse et al., 2010; Arhan et al., 2011), where they likely fail to impact the AMOC. Therefore, a key question still remains on the table: were the observed maxima in AL eventually incorporated in the South Atlantic gyre, thus forming the waters that subsequently cross the equator through the North Brazil Current? To postulate that stronger AL effectively influenced the AMOC strength demands this paleo connection, between the eastern Cape Basin and the South Atlantic circulation, to be drawn.

Here we test this case upon the penultimate deglaciation (termination II, T II), since it is characterized by a very distinguished peak in AL in the Pleistocene reconstruction of Peeters et al. (2004) (Fig. 3b). Our hypothesis is rationalized as follows. Regardless of the form that it assumes - either rings or filaments – the AL introduces anomalies in the temperature and salinity fields of the South Atlantic subtropical gyre. It is of high interest to both paleoclimatology and modern oceanography communities to know whether such perturbations were present over the central Walvis Ridge, almost 1800 km further downstream into the Atlantic Ocean, and with which intensity, under different climatic frameworks.

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Modern analytic techniques enable us to investigate such anomalies, by means of geochemical analysis of microfossils from marine sediment. By selecting the appropriate species of planktic foraminifer, we aim to target water masses at the depth of the thermocline, where variability due to AL should be maximal (Souza et al., 2011).

Recently, paleoceanographic research has started to employ the oxygen isotope composition (δ^{18}O) of single foraminifera specimen, to address questions related to variability. For instance, Billups and Spero (1996) and Ganssen et al. (2011) used single shell analyses to unravel the range of hydrographic conditions in the Equatorial Atlantic and in the Arabian Sea, respectively, while Koutavas et al. (2006) and Leduc et al. (2009) applied the approach to capture ENSO extremes in the Eastern Equatorial Pacific.

1.3 Rings path and core selection

The path undertaken by Agulhas rings has been the focus of many studies (e.g. Olson and Evans, 1986; Dencausse et al., 2010; Schouten et al., 2000). The SAVE 4 section in years 1989–1990 encountered two Agulhas rings at the central Walvis Ridge, at about 30° S (Gordon et al., 1992). Satellite data (Gordon and Haxby, 1990; Boebel et al., 2003) make it clear that such location is in the full trajectory of rings. Generally, topography seems to be decisive for the displacement of eddies in the Cape Basin (Matano and Beier, 2003; Boebel et al., 2003), and some of the deep canyons in this ridge possibly steer the passage of rings (Byrne et al., 1995; Dencausse et al., 2010; van Sebille et al., 2012). This body of knowledge led us to choose the central Walvis Ridge as an appropriate setting to test our hypothesis.

In addition, we use a high-resolution global ocean circulation model to illustrate that our sediment core is exactly underneath the path of Agulhas rings in present climate, and that the passing of rings is indeed characterized by anomalously low densities at the depths that we study with our foraminifer taxon.

2 Methods

2.1 Isotope analysis

We conducted analysis on core 64PE-174P13, lifted from the central Walvis Ridge (29°45.71′ S, 2°24.10′ E) at the depth of 2912 m (Fig. 1). From it we selected 18 sediment samples that overarch ~ 70 thousand years (ka) between Marine Isotope Stage (MIS) 6 and 5, based on the stratigraphy of Scussolini and Peeters (2013), which is anchored to the LR04 marine isotope stack (Lisiecki and Raymo, 2005). Additionally, we selected two samples, from the core top and from 2 cm in the sediment, that are representative of near-modern conditions. For each sample, between 18 and 30 specimen of *Globorotalia truncatulinoides* sinistral (left coiling variety) were picked from the size fraction 250–300 µm, to constrain the depth of calcification. We selected this taxon due to its extensively studied depth habitat (e.g. Lohman and Schweitzer, 1990; Mulitza et al., 1997; LeGrande et al., 2004), which for this location we quantified around 500 m (Scussolini and Peeters, 2013), thus befitting our plan to target the thermocline. A total of 478 isotopic measurements on individual shells were performed at the VU University, Amsterdam, with the method described in Scussolini and Peeters (2013). The average reproducibility on external standards was better than 0.10 ‰.

Since we are specifically interested in assessing the variability between measurements within samples, it is essential that the typical inter-run fluctuations in instrumental precision do not bias the estimation. For this reason, we corrected the variance of foraminifera δ^{18}O by subtracting that of external standards measured along with them, as recommended by Killingley et al. (1981) (Table 1).

2.2 Model data set

The model data set we incorporate in our study comes from global full-depth fields of the Cube92 run of the assimilative ECCO2 project. This project combines observations of global ocean and sea-ice, both in situ and from satellite data, with a state-of-the-art

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numerical model in order to obtain a time series of high-resolution ocean velocity, temperature, and salinity as close to the observations as possible. The model used is the MITgcm (Marshall et al., 1997) and the data are synthesised using a Green's function method (Menemenlis et al., 2005).

The model output spans 20 yr (from 1992 to 2012) and has a cube sphere projection with a mean horizontal resolution of 18 km. There are 50 vertical levels ranging in thickness from 10 m at the surface to 456 m at depth. To facilitate analysis, the model data used in this study were regridded to a globally uniform 1/4° grid. The skill of the ECCO2 model in simulating the global circulation has been demonstrated in several studies, for instance, on the AMOC (Baehr et al., 2009).

3 Results

3.1 Variability of *G. truncatulinoides* sin. single specimen

The corrected variability of *G. truncatulinoides* sin. samples changes along the transition from MIS 6 to 5 (Table 1; Fig. 3). It increases from ~145 ka before present (BP) to ~130 ka BP, hence returning more rapidly to levels similar to full-MIS 6 ones at ~123 ka BP, after which it remains stable for at least 20 ka.

The values of the two near-modern samples are in line with those from early MIS 5, with the most recent one being lower than at ~2 ka BP. This appears as a confirmation that, as in the penultimate cycle, variability decreases from the beginning of the interglacial.

3.2 Effect of Agulhas rings on the central Walvis Ridge water column

Analysis of the ECCO2 time series for the South Atlantic basin shows that the variability of sea surface height (SSH), a proxy for Agulhas rings (van Sebille et al., 2012), and of potential seawater density (σ_θ) at 477 m depth are tightly connected, with a tongue of maximum values extending far into the gyre from the Agulhas retroflection area (Fig. 1).

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The core location is found in this area of high variability of the plotted parameters. Further, we are able to describe the changes in ~500 m water properties that Agulhas rings bring about above our setting, by recognizing their passage in the 20 yr series of SSH (Fig. 2d). In the model layer at 477 m, rings are characterized by peaks of temperature and salinity, and by troughs of density. It is important to note that the effect of temperature overrides that of salinity in determining density within a ring, coherently with the observations of Giulivi and Gordon (2006) and Arhan et al. (2011). We can attribute the largest density troughs to Agulhas rings that fully overshadow the core setting (Fig. 2b), and the minor ones to ring flanks moving over it (Fig. 2a). It is hence possible to ascertain that out of the six Agulhas rings typically released per year, core 64PE-174P13 presently captures on average one full ring, plus a slightly smaller figure of ring flanks.

4 Discussion

From our analysis of the model series (Figs. 1 and 2) we are able to determine that, in the South Atlantic, a high frequency of Agulhas rings, as seen from the SSH, dictates enhanced variability in pycnocline depth, at the depths where *G. truncatulinoides* sin. records its δ^{18}O.

The pattern of SSH variability in ECCO2 (Fig. 1) is somewhat more confined than seen in observations (e.g. Biastoch et al., 2008a; Van Sebille et al., 2010a), suggesting that ECCO2 has a slight bias in the spread of Agulhas ring pathways. However, we do not expect this small potential bias to invalidate our reasoning. A broader tongue of SSH variability in the real ocean would still imply that the core lies directly underneath the preferential pathway of Agulhas rings, so that our variability peak can positively be related to increased frequency of Agulhas rings, and ring flanks.

Temperature and salinity changes forced by seasonality upon the southeast Atlantic do not reach the depths of *G. truncatulinoides* sin. main calcification. At T II, the isotope curve of bulk δ^{18}O measurements (Scussolini and Peeters, 2013) (Fig. 3a) exhibits a rather sharp change in values, of ~1.46‰, which warrants ruling out concerns about excessive bioturbation promoting sediment mixing (e.g. Broecker, 1986), to the extent required to generate the observed variability peak. Therefore, the phenomenon of increased variability, in such fully pelagic setting, directly invokes the passage of perturbatory bodies in a field of relatively stable hydrographic conditions.

Inasmuch as foraminiferal δ^{18}O is a function of seawater density (e.g. Lynch-Stieglitz et al., 1999), and in particular *G. truncatulinoides* was found to capture intermediate depth density (LeGrande et al., 2004), we have generated a reconstruction of pycnocline depth variability for the central Walvis Ridge, which we consider to be a paleo proxy for the presence of Agulhas rings/AL.

In this view, more AL reaches the west flank of the Cape Basin as MIS 6 draws to its end, and the influence is maximal right at T II, likely higher than observed in the modern ocean (Table 1, Fig. 3b). This signal can be interpreted as the passage of more Agulhas rings, or of larger and more stable ones, that linger over the core site for a longer time. Both possibilities point at a stronger AL. Still, the latter seems corroborated by another finding: rings of greater size and stability have been connected to larger variability in the position of Agulhas retroflection (van Sebille et al., 2009). This scenario is particularly plausible at times of climate shift such as T II, when the system of fronts south of Africa was supposedly more dynamic, likely due to meridional shifts in the wind field (Hays et al., 1976; Bé and Duplessy, 1976; Bard and Rickaby, 2009; Biastoch et al., 2009).

We compare the timing of our observations to the published records of Agulhas Leakage fauna (a proxy for AL) from the eastern Cape Basin, of Peeters et al. (2004) and Martínez-Méndez et al. (2010) (Fig. 3b). For this purpose, we rendered the age of those records compatible with the chronology of our core, by aligning the respective benthic δ^{18}O curves to the LR04 stack. The remarkable agreement between our variability record and the AL fauna answers the initial question whether the AL peak at T II penetrated the South Atlantic circulation. Furthermore, it seems clear that the phenomenon intensified already before maximum glacial conditions. Although our age control is not adequate to accurately date the start of the AL increase, this points at

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an active role of the southern hemisphere in the series of mechanisms leading to the termination, as recently proposed in the scenarios of Cheng et al. (2009) and Denton et al. (2010).

While we can consider that AL observed at the central Walvis Ridge has been incorporated in the sub-tropical gyre circulation, it does not directly follow that those waters have made it to the North Brazil Current, and therefore into the North Atlantic. High-resolution ocean models showed that changes in the amount of AL in the Cape Basin do not directly lead to changes in the amount of Indian Ocean water crossing the Equator in the Atlantic (Biastoch et al., 2009; Biastoch and Böning, 2013). However, the salt flux of the North Brazil Current (Biastoch et al., 2008b), as well as the intensity of the AMOC (Biastoch and Böning, 2013), seems to be related to the strength of AL.

Therefore, even if little of the extra AL had made it into the North Atlantic, it could still have imposed an effect on the strength of the AMOC. Authors such as Weijer et al. (2002) have shown that the strength of the overturning circulation is, to a large extent, determined by the pressure gradient between the southern and northern Atlantic. Increased AL could, even if mostly recirculating in the supergyre (e.g. Gordon et al., 1992; Speich et al., 2007), change the meridional density and hence pressure gradients, and thereby the strength of the AMOC. Furthermore, van Sebille and van Leeuwen (2007) found that the baroclinic energy from Agulhas rings in the South Atlantic Ocean can be radiated to the North Atlantic and affect the strength of the overturning there, even if no mass is transported across the equator.

In other terms, our core on the central Walvis Ridge likely witnessed the AL resuming again before T II, thus lending important support to the idea of its prominent role in restoring the intensified interglacial mode of the conveyor belt (Gordon et al., 1992; Berger and Wefer, 1996; Weijer et al., 2002; Knorr and Lohmann, 2003).

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5 Conclusions

We have presented a novel application for the seldom-utilized analysis of isotopes in single specimen of foraminifera. The method can be conveniently used to unravel paleoceanographic aspects beyond the average state of physicochemical quantities, and in particular to test hypotheses relative to mixing of water masses with different characteristics.

In this study, we assessed the paleo-variability in the $\delta^{18}O$ of a thermocline-dwelling taxon, thereby observing substantially higher density anomalies investing the South Atlantic gyre, prior to and at glacial Termination II. Backed by a high-resolution assimilative ocean circulation model, we are able to interpret such anomalies as the passage of Agulhas rings, or other leakage features, spawn from the Agulhas Current retroflection. The evidence we present fills a gap between the increase of AL recorded around terminations at the interface between the Indian and the Atlantic Oceans, and its incorporation downstream in the South Atlantic gyre, and hence in the supergyre. Such connection is necessary to bolster the current hypothesis of the primary role played by the AL, in the transition from superficial glacial to vigorous interglacial AMOC, either as an active mechanism or rather as a passive feedback trigged by meridional displacement of wind fields.

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Paleo Agulhas rings enter the subtropical gyre

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Table 1. Result of the individual specimen isotope measurements, and estimation of sample variability, and the respective correction (see Sect. 2).

Sample depth (cm)	Age (ka BP)	*N* specimen	Instrument s^2	Sample s^2	Corrected s^2
0	~ 0	28	0.025	0.350	0.325
2	2.0	18	0.003	0.573	0.570
120	104.4	29	0.004	0.074	0.070
124	112.2	28	0.015	0.106	0.091
129	119.7	19	0.009	0.047	0.038
131	120.6	17	0.012	0.087	0.075
136	122.7	21	0.003	0.142	0.139
142	125.3	20	0.025	0.274	0.249
146	127.6	20	0.006	0.440	0.434
150	130.7	20	0.006	0.421	0.415
154	132.9	19	0.012	0.482	0.470
156	133.9	20	0.009	0.368	0.359
160	138.0	19	0.009	0.320	0.311
164	142.7	20	0.009	0.178	0.169
168	147.4	21	0.009	0.119	0.110
172	152.1	20	0.006	0.226	0.220
176	155.9	30	0.015	0.122	0.107
182	158.7	20	0.012	0.061	0.049
184	159.7	18	0.009	0.183	0.174
188	161.6	19	0.025	0.162	0.137
194	164.4	21	0.003	0.101	0.098
202	170.1	28	0.004	0.067	0.063

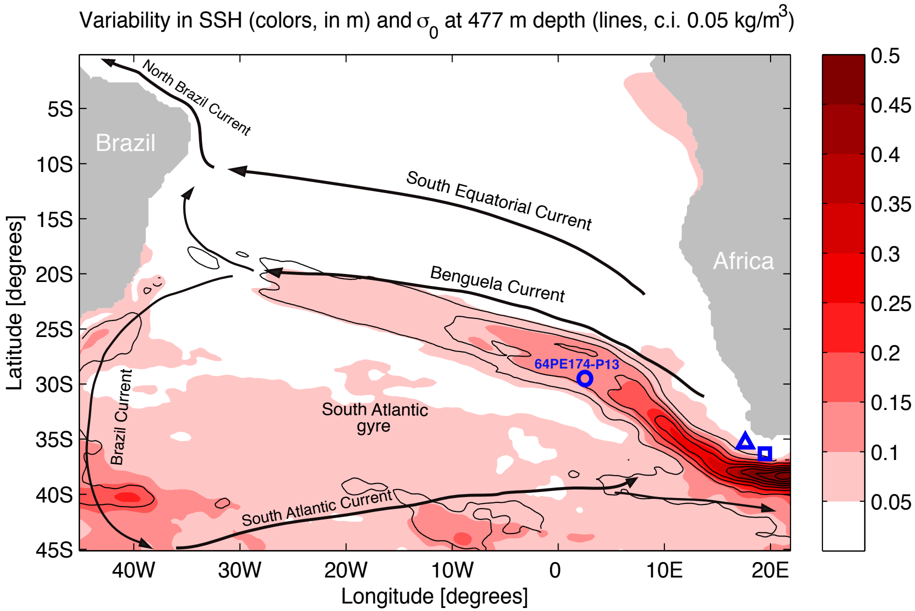

Fig. 1. Map of the Southeast Atlantic, with location of the core studied here (blue circle), of the Cape Basin record (triangle) of Peeters et al. (2004), and of the Agulhas Bank Splice (square) of Martínez-Méndez et al. (2010). Also indicated are contoured variabilities of both SSH (colors) and of σ_θ at the 477 m depth model level (lines) over the basin, in the ECCO2 model (see Sect. 2). Arrows denote currents at the depth of South Atlantic Central Waters.

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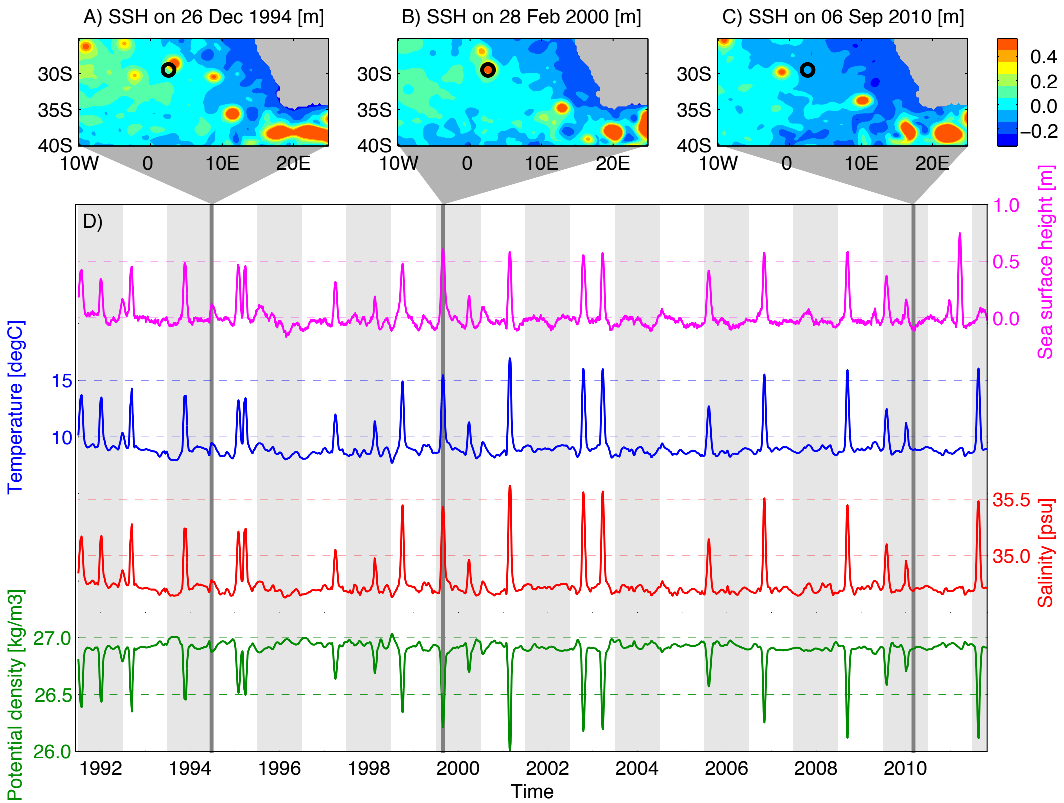

Fig. 2. Analysis of model ECCO2 output. **(A)**, **(B)**, and **(C)**: SSH maps showing the position of Agulhas Rings with respect to the core location, in three selected situations recurring in the time series **(D)** of SSH, temperature, salinity and density at 477 m, for the period 1992–2012. **(A)** partial overlap (small perturbation in the series); **(B)** full overlap (peak); **(C)** no ring in proximity (steady background).

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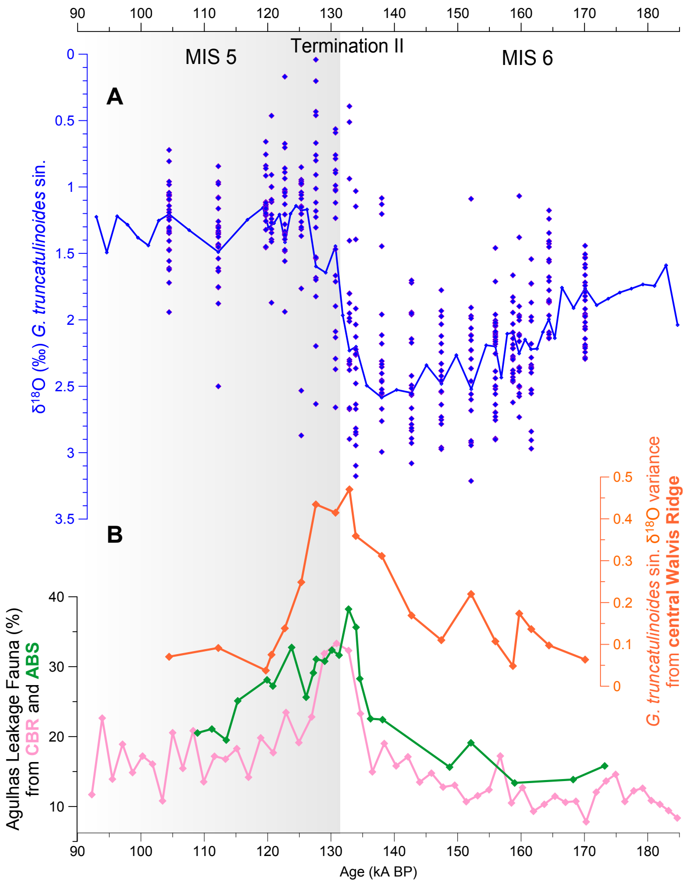

Fig. 3. (A) δ^{18}O of *G. truncatulinoides* sin. single specimen (blue diamonds) and bulk analysis (blue line, Scussolini and Peeters, 2013). **(B)** Corrected sample δ^{18}O variance (orange, see Methods); estimation of AL from the Cape Basin record (CBR, Peeters et al., 2004) (pink) and from the Agulhas Bank Splice (ABS, Martínez-Méndez et al., 2010) (green).

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