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Regional circulation and its impact on upper ocean variability south of Tasmania

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ABSTRACT

Ocean colour images of the Subantarctic Zone (SAZ) south of Tasmania show a higher biomass in the east than in the west. To identify the main features of the regional circulation and the physical drivers of the east/west contrast, we used World Ocean Circulation Experiment hydrographic sections SR3 and P11S (west and east of Tasmania, respectively), Argo float profiles and trajectories, and high resolution climatology. The East Australian Current and the Tasman Outflow are the mechanisms driving the variability in the eastern Subantarctic Zone. This region has a weak flow and an enhanced input of subtropical waters through eddies, interleaving and a subsurface salinity maximum intruding from the north to south. In the western Subantarctic Zone, the regional circulation is dominated by a northwestward circulation and a deep reaching anticyclonic recirculation. The South Tasman Rise acts as a barrier, inhibiting exchange between waters southeast and southwest of Tasmania. The regional circulation and mixing processes result in the strong contrast in water properties between the eastern and western Subantarctic Zone: cooler and fresher in the west and warmer and saltier in the east. The Subantarctic Mode Water (SAMW) pycnostad is more prominent in the west, with a local variety of SAMW associated with the anticyclonic recirculation west of the South Tasman Rise. Antarctic Intermediate Water (AAIW) formed in the southeastern Pacific and southwestern Atlantic Oceans meet in the SAZ south of Tasmania. Cool, fresh, and well-ventilated AAIW is found in the west and southeast SAZ. Relatively warm, salty and low oxygen AAIW enters the SAZ from the Tasman Sea, after having traversed the Pacific Ocean subtropical gyre. Enhanced input of subtropical water high in micronutrients (such as iron) in the east likely supports the higher surface biomass observed there. The physical processes responsible for maintaining the east/west contrast south of Tasmania (e.g. regional circulation, eddies and intrusions) are likely to drive variability in physical and biogeochemical properties of SAMW, AAIW, and the Subantarctic Zone elsewhere in the Southern Ocean.

1. Introduction

The Southern Ocean plays a major role in global climate and global biogeochemical cycling. It is a key component of the overturning circulation, where deep water upwells and is transformed into mode and intermediate waters that ventilate part of the global ocean. These transformed water masses also contribute to global heat, freshwater, carbon, and nutrient budgets. The Subantarctic Zone (SAZ), bounded by the Subtropical Front (STF) and the Subantarctic Front (SAF), is the region of the Southern Ocean with the largest zonally integrated inventory of anthropogenic carbon dioxide (McNeil et al., 2001; Sabine et al., 2004). Biological production in the SAZ drives a strong seasonal cycle of dissolved nutrient and carbon dioxide concentrations on the surface and a large net uptake of carbon dioxide from the atmosphere (Metzl et al., 1999; Lourey and Trull, 2001; Wang et al., 2001) which is accompanied by the export of organic carbon in sinking particles (Trull et al., 2001).

The properties of the SAZ vary around the circumpolar belt (Hanawa and Talley, 2001; McCartney, 1977), particularly in the interaction with subtropical waters. However, the relative importance of air–sea fluxes, regional circulation, and exchanges across the STF and SAF on water mass properties in the SAZ is unclear. The SAZ-Sense project[1] sought to characterize the key components of the Southern Ocean planktonic community, with a focus on the SAZ, and examine their role in transferring carbon dioxide

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[1] www.cmar.csiro.au/datacentre/saz-sense/.

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from the surface to the deep ocean. The region east of Tasmania (150–160°E) generally has a relatively large phytoplankton surface biomass and productivity, in contrast with the lower surface biomass in the west (135–145°E) (Trull et al., 2001; Bowie et al., 2011). This contrast in surface biomass is clearly seen in ocean colour satellite images (Bowie et al., 2011). The Tasman Sea, situated along the eastern coast of Australia, shows some of the highest rates of temperature change observed in the Southern Hemisphere (Hill et al., 2008) and in global circulation model simulations of greenhouse-gas driven climate warming (Cai et al., 2005). A southward shift of the westerlies might already have changed atmospheric and oceanic circulation, strengthening the influence of subtropical waters in the SAZ (Poloczanska et al., 2007; Ridgway, 2007a; Hill et al., 2008), especially to the east of Tasmania. Therefore, the Tasmanian sector of the SAZ provides a natural context within which to identify, describe, and evaluate the response of subantarctic ecosystems to changes in the environment.

Two intermediate water masses are found in the upper ocean in the SAZ, Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) (Hanawa and Talley, 2001). SAMW is a thick, homogeneous layer formed by deep convection in winter in the SAZ (McCartney, 1977). The interaction of the SAF with the SouthEast Indian Ridge creates numerous eddies and meanders which can influence the properties of the SAMW formed just north of the SAF (Herraiz-Borreguero and Rintoul, 2010). AAIW is a low-salinity water mass that occupies most of the Southern Hemisphere and the tropical oceans at intermediate depths (800–1200 m). SAMW and AAIW ventilate the main oceanic thermocline and contribute to large-scale fluxes and budgets of heat, freshwater, carbon dioxide, and nutrients. For example, Sarmiento et al. (2004) suggested that the nutrients supplied by SAMW ultimately supported 75% of the export production north of 30°S. Understanding the mechanisms involved in setting the properties of the SAZ is important for improving our knowledge of SAMW, and vice versa.

The main regional circulation features south of Tasmania are shown in Fig. 1. Cresswell (2000) described the major currents over the slope and continental shelf around Tasmania, namely the Zeehan Current and the East Australian Current (EAC). The Zeehan Current flow is restricted to waters over the western Tasmanian continental shelf and upper slope and it is stronger during winter. It flows southward along western Tasmania to turn and run northward off eastern Tasmania where it deflects the EAC to the east creating many mesoscale features. Although most of the EAC separates from the coast and flows to the east around 32°S, some flow (termed the EAC Extension) continues southward along the coast, reaching the east coast of Tasmania during summer. When it reaches the southeast point of Tasmania, it interacts with the Zeehan Current and the South Tasman Rise, limiting the southwest extent of the EAC waters. The seasonal circulation around Tasmania is described in detail by Ridgway (2007b).

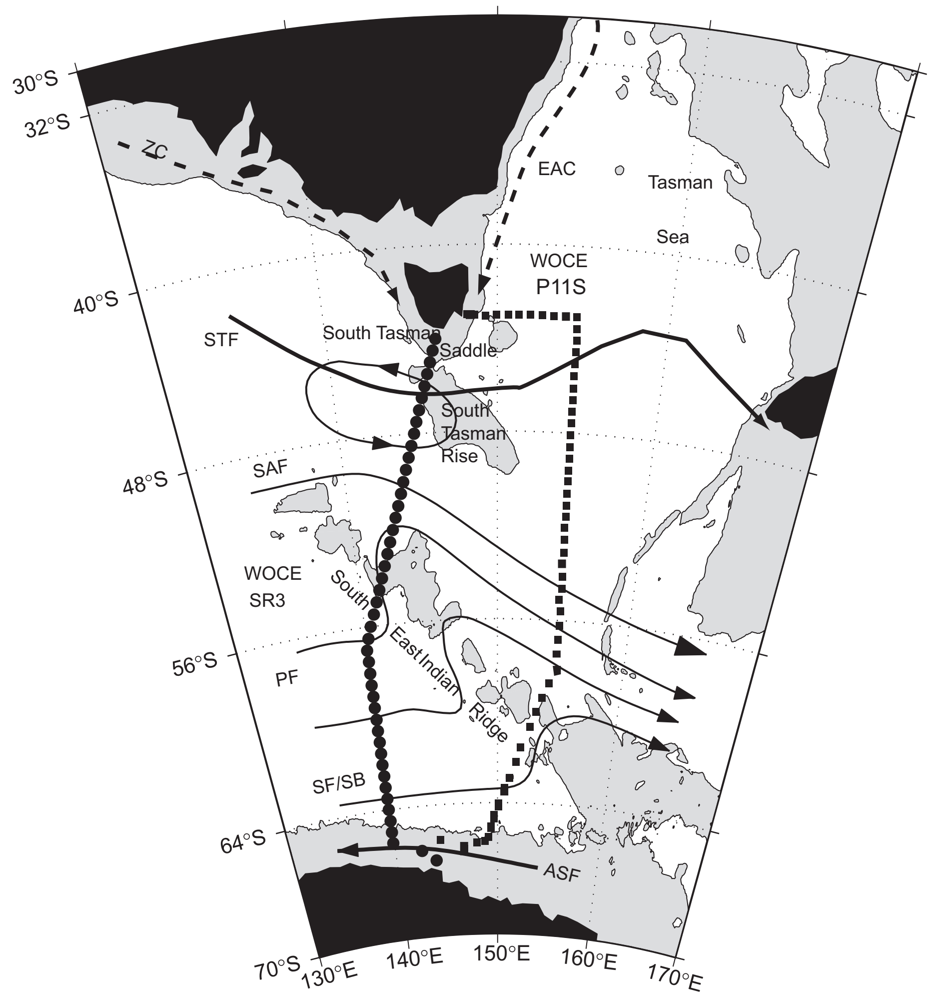

Fig. 1. Summary of the main features for the regional circulation south of Tasmania. World Ocean Circulation Experiment sections, SR3 and P11S. EAC, extension of East Australian Current; ZC, Zeehan Current; STF, Subtropical Front; SAF, Subantarctic Front; PF, Polar Front; SF, southern ACC front; SB, southern boundary of the ACC; ASF, Antarctic Slope Front. Bathymetry higher than 2000 m appears as shaded contours. The SAZ-Sense project focuses mainly in the Subantarctic Zone: region delimited by the STF and the SAF.

Rintoul and Sokolov (2001) documented two major circulation features in the vicinity of the SAZ: (i) West of the South Tasman Rise, a deep-reaching anticyclonic recirculation is located between ~47°S and 49°S. (ii) East of Tasmania, a weak northward flow enters the Tasman Sea, turns anti-clockwise to flow southward along the Tasmanian coast, and passes westward through the South Tasman Saddle (the relatively deep channel (3500 m) that separates the South Tasman Rise from the continental slope of Tasmania). Our results suggest a slightly different interpretation of the flow in this region, as discussed in Section 4.

The goal of the present study was to assess the influence of the regional circulation on the water properties and biomass differences observed east and west of Tasmania. This study has broad implications because these same processes may affect SAMW, AAIW, and SAZ variability elsewhere. The study also provides new information on the nature of the exchange between the Pacific Ocean and the Indian Ocean south of Australia (Speich et al., 2002; Ridgway and Dunn, 2007; Cai et al., 2005).

The paper is structured as follows. Sections 2 and 3 describe the data used and the temperature–salinity distributions in the water column, focusing on the main water masses, SAMW and AAIW. The regional circulation inferred from Argo float trajectories and its relationship with the distribution of water mass properties is discussed in Section 4. Our findings are summarized in Section 5.

2. Data

2.1. World Ocean Circulation Experiment (WOCE) transects

Two late-summer CTD transects were collected during voyages of the research vessel R.S.V. *Aurora Australis* in March–April 1993 (SR3 and P11S) (Fig. 1). Stations along the sections were generally about 55 km apart in the Subantarctic Zone, both southwest (SR3) and east (P11S) of Tasmania. They provide a good reference to locate the two main water masses in the SAZ: SAMW and AAIW, which are described in Section 3. Useful information on the SR3 sections can be found by Rintoul and Bullister (1999), Sokolov and Rintoul (2002), and Rintoul et al. (2002).

2.2. Argo

The vertical structure of the water column in the South Tasman Sea and Subantarctic Zone (SAZ) south of Tasmania was obtained from the Argo data set, which provides data covering vast areas of the Southern Ocean for the first time. Data are made freely available by the International Argo Project and the national programs that contribute to it. In the SAZ, south of Tasmania, around 200 Argo floats have been deployed, providing more than seven thousand temperature and salinity profiles of the top 2000 m. This study used

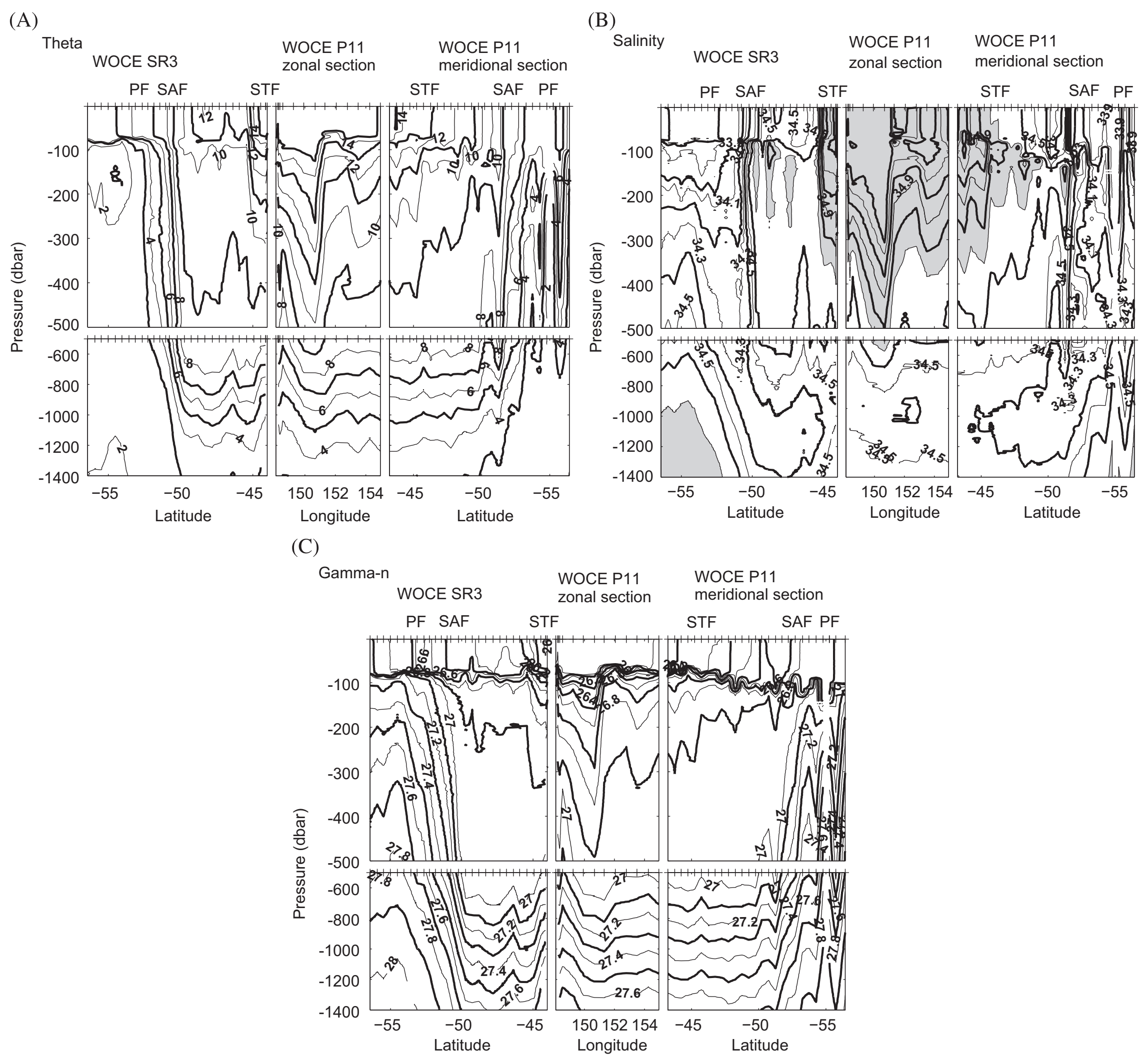

Fig. 2. Property distributions along sections P11S (zonal and meridional legs) and SR3: (A) potential temperature, θ; (B) salinity, where shaded contours represent salinity values higher than 34.7 psu; and (C) neutral density (γ^n) (kg m^{-3}). The locations of the major fronts are indicated above: STF, Subtropical Front; SAF, Subantarctic Front; PF, Polar Front. Upper ticks depict the sampled stations.

delayed-mode profiles that passed the Argo quality control, with data on their position, date, temperature and salinity from 10 to 1800 m.

3. Water mass properties

Vertical sections of potential temperature, salinity, and neutral density from SR3 and P11S show the main vertical structure of the water column in the SAZ (Fig. 2, SR3, left; P11S, middle and right). The region of the SAZ-Sense project is affected by three fronts: the Subtropical Front (STF), the Subantarctic Front (SAF) and the Polar Front. The STF represents the boundary between warm, salty subtropical waters and cold, fresh subantarctic waters. In this region, the STF coincides with the crossing of the 11 °C isotherm at 150 m depth and the southern limit of the water with salinity greater than 34.8 psu (Nagata et al., 1988; Sokolov and Rintoul, 2002). The SAF, which is the strongest front of the Antarctic Circumpolar Current south of Australia (Sokolov and Rintoul, 2002), is marked by the presence of a thermostad (the SAMW) and a salinity-minimum layer (the AAIW) to the north. The Polar Front is commonly defined by the northernmost extent of the subsurface temperature-minimum cooler than 2 °C near 200 m depth (Belkin and Gordon, 1996). It is marked by a transition to very cold, relatively fresh, Antarctic Surface Water at the surface. The locations of the fronts are indicated above the plots in Fig. 2.

The eastern SAZ receives inputs of warm and salty waters through two mechanisms: the East Australian Current (EAC) extension and the Tasman Outflow. The EAC extension is a southward flow along the eastern shore of Tasmania (Cresswell, 2000), seen in the steeply sloping temperature, salinity and neutral density contours at ~149–151°E (Fig. 2A–C, upper middle panel). The Tasman Outflow (a remnant of the EAC at intermediate depths) reaches the south Indian Ocean as a relatively warm and salty flow. It also provides an additional component of the thermohaline circulation and a southern connection between the Pacific and Indian Oceans (Rintoul and Bullister, 1999; Speich et al., 2002; Ridgway and Dunn, 2007). The western SAZ shows properties more typical of the circumpolar SAZ: relatively cold and fresh, and less influenced by warm, salty, subtropical waters than the eastern SAZ. The top 200 m of the water column on P11S is warmer and saltier than that on SR3. A subsurface salinity intrusion, found in both sections, is more prominent at P11S (Fig. 2B).

SAMW and AAIW occupy most of the upper ocean in the SAZ. South of Tasmania, SAMW forms a thick pycnostad (thus, minimum in potential vorticity) with a core temperature of 8.5–9 °C and salinity of 34.55–34.70 psu, and a high oxygen concentration. In the western hydrographic section (SR3), the upper and lower bounds of the SAMW pycnostad reach mean depths between ~190 and 600 m, while in the eastern section, the upper and lower bounds are between ~170 and 500 m. The oxygen concentration in the SAMW pool west of Tasmania is uniformly high; while in the east, oxygen concentrations decrease from south to north within the SAMW pool (not shown here). AAIW has a much lower oxygen concentration than SAMW. It is identified as a salinity minimum at intermediate depths north of the SAF and below SAMW (Fig. 2B). South of Tasmania, the salinity minimum is not uniform in its properties, corresponding to a range of temperature and density: water with salinity less than 34.4 psu spans the range 27.25–27.6 kg m^{-3} in neutral density and 3.43–5.63 °C in temperature (Rintoul and Bullister, 1999).

A review of the water mass properties, their distribution, and the relationship with the regional circulation in the area is given below, starting with the properties east and west of Tasmania.

3.1. Temperature–salinity properties east and west of Tasmania

The distribution of the physical properties in the water column in and around the SAZ were studied using Argo float potential temperature (θ) and salinity (S) profiles. To get an overview of the mean potential temperature and salinity properties and their origin, we divided the region into seven boxes (Fig. 3). We focus on the salinity minimum to describe the main differences.

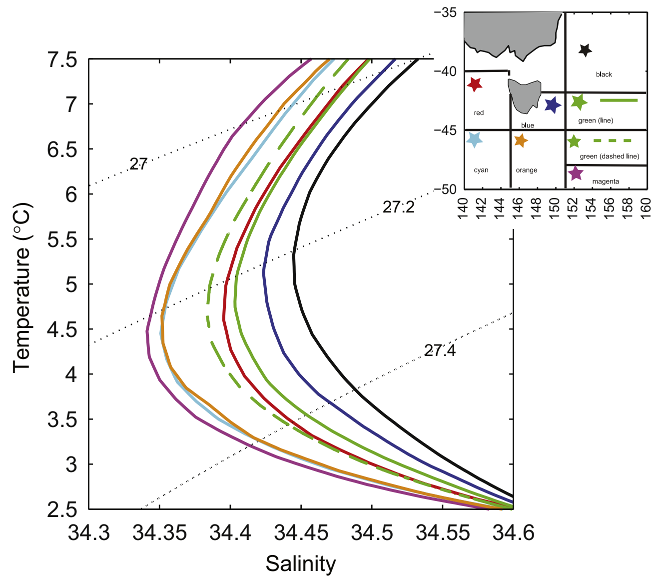

Fig. 3. Mean potential temperature–salinity (θ–S) at the salinity minimum from Argo profiles. Each colour represents a box in the map (top right). Black dotted lines are potential density contours.

The θ–S curves span a wide range of properties even in this relatively small region, with a salinity difference of 0.1 psu between the freshest and the saltiest salinity minimum values. The extreme θ–S curves represent the two main regions influencing the water-mass properties in the SAZ. The saltiest and lightest S-minimum is in the southern Tasman Sea, north of 43°S (Fig. 3, black curve). The freshest and densest S-minimum is found along the SAF (Fig. 3, cyan, orange, and magenta curves), reflecting the dominant influence of Southern Ocean waters on the physical properties of these three boxes. These southern waters change little from west to east. Intermediate S-minimum values from the middle boxes show stronger Tasman Sea input in the east, in particular near the southeast coast of Tasmania (blue curve), where the influence of the EAC is greatest.

3.2. Subantarctic Mode Water (SAMW)

The CTD profiles from the WOCE hydrographic sections and the profiling floats were used to study the SAMW distribution in detail. In order to use as many Argo profiles as possible and avoid dealing with seasonality, the top 200 dbar were not used. SAMW was defined as water with potential vorticity (PV) less than 1×10^{-9} m^{-1} s^{-1} and potential temperature (θ) between 8 and 9 °C for depths greater than 200 dbar. The potential vorticity for a fixed depth interval of ~40 m was calculated as

$$PV = \frac{f}{\rho}\frac{d\rho}{dz}$$

where f is the Coriolis parameter, ρ is the potential density, and z is the depth.

The distribution and circulation of SAMW is illustrated by plotting the thickness of the SAMW layer and Montgomery streamfunction (Montgomery, 1937) on the γ^n=27 surface (Fig. 4, top). SAMW thickness was calculated as the difference in pressure between the top and bottom of the SAMW layer defined by our PV minimum range at each profile. Zhang and Hogg (1992) showed

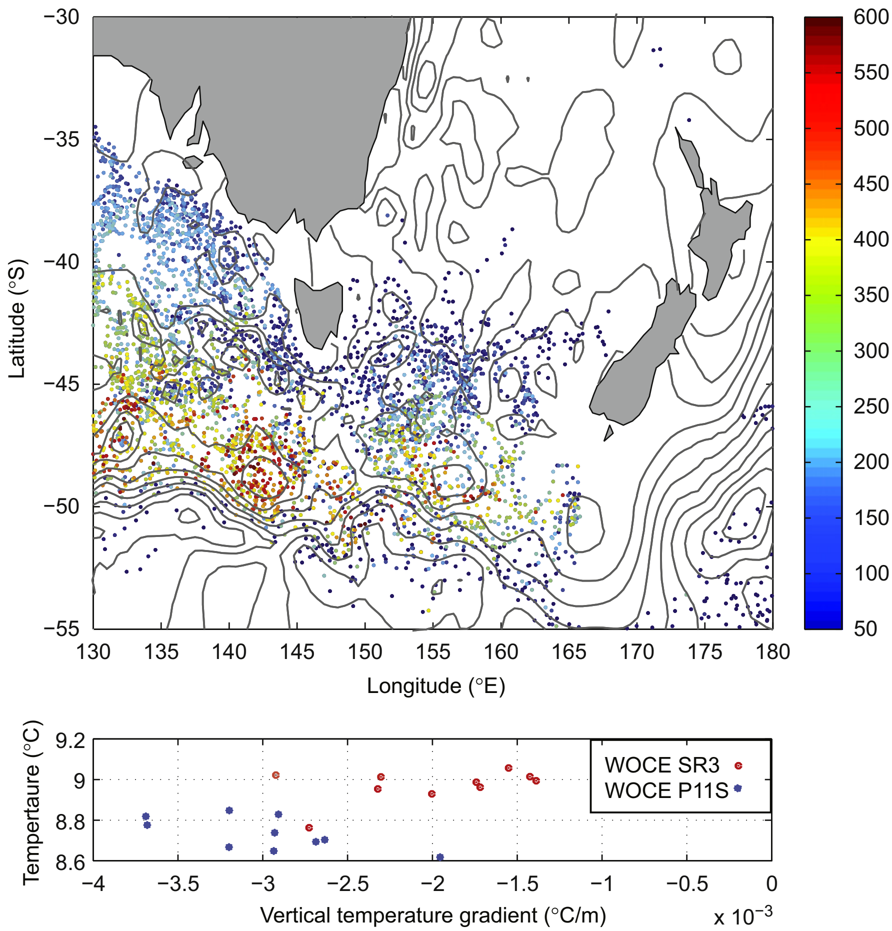

Fig. 4. SAMW thickness (dbar) (top). Montgomery streamlines ($m^2\,s^{-2}$) were calculated for $\gamma = 27$ kg m^{-3} corresponding to the SAMW density at the bottom of the pycnostads (black lines). SAMW thermostads strength ($d\theta/dz$) found at SR3 and P11S (bottom) (red and blue, respectively).

that the geostrophic streamlines on potential density surfaces may be approximated by the Montgomery streamfunction on a surface of constant specific volume anomaly, δ, so that

$$M = \hat{\delta}(z)(p(z) - \hat{p}) + \int_0^Z \hat{\delta}(z)\,dp$$

where z represents the depth of the isopycnal surface and varies spatially, and $\hat{p}$ is the median pressure at the isopycnal surface. $\hat{\delta}(z)$ is define as

$$\hat{\delta}(z) = \frac{1}{\rho(z)} - \frac{1}{\rho_o}, \quad \rho_o = \rho(\hat{S}, \hat{T}, z)$$

where ρ represents the *in situ* density and ρ_o is the density of a reference fluid. Here we defined $\hat{S}$ and $\hat{T}$ as the median values on the isopycnal surface. We have based our analysis on neutral density surfaces. We used a reference pressure of 1800 dbar to provide a good balance between retaining the deepest profiles and having the maximum number of Argo profiles.

Mode water forms either side of Tasmania in the SAZ, but the SAMW properties are different in the east and the west. The SAMW layer is much thinner in the east than in the west (Fig. 4). The thermostad is also stronger (more vertically uniform) in the west (Fig. 4, bottom). Winter convection appears to less effectively homogenise the water column in the SAZ east of Tasmania. The extent and depth of the deep convection that forms mode water depends on the buoyancy loss to the atmosphere, the stratification, and regional circulation. The stratification, in turn, can be influenced by exchange with the subtropics (e.g. through interleaving, intrusions and eddies). The SAMW thickness in the area labelled in green in the inset of Fig. 3 (43–47°S, 151–160°E) is 250–300 dbar, about 100 dbar less than observed further south in the SAZ (Fig. 4, top).

The distribution of the pycnostads associated with SAMW is strongly influenced by the regional circulation, as revealed by the Montgomery streamfunction (Fig. 4). The South Tasman Rise seems to separate regions with different circulation patterns: on the eastern side, the circulation seems to be very slow, while on the western side, there is an anticyclonic circulation south of 43°S. The thin SAMW pool in the east and thick pool in the west are separated by the South Tasman Rise. Thick SAMW is found in the northwestward anticyclonic flow, with the thickest SAMW pool embedded in the closed anticyclonic recirculation described by Sokolov and Rintoul (2002) (Fig. 1, closed contour centred at about 48°S and 143°W). Also, thick SAMW layers are found just north of the SAF.

3.3. *Antarctic Intermediate Water (AAIW)*

In Section 3.1, we showed that the properties of the salinity minimum defining AAIW varied strongly across the region, with low salinity AAIW ($S \leq 34.4$ psu) in the south and high-salinity AAIW ($S \geq 34.4$ psu) in the north. The high-salinity AAIW is formed in the southeast Pacific and is carried around the subtropical gyre to enter the Tasman Sea between New Zealand and Fiji (Wyrtki, 1962; Sokolov and Rintoul, 2000). This variety of AAIW extends as far south as 40°S, where the median properties are 34.44 psu and 5 °C (Fig. 3, black θ–S curve). South of ~40°S, this northern AAIW mixes with waters from the Subantarctic Zone, and decreases its salinity. The neutral density (γ^n) distribution for salinity minimum layers with S less than 34.4 psu peaks at γ^n=27.4 kg m^{-3}. Fig. 5 shows the temperature and salinity distribution at this density surface. Relatively warm, salty AAIW extends southwestward and through the South Tasman Saddle (Fig. 5, orange dots). A cooler, fresher variety of AAIW enters the SAZ from the south, with median properties of salinity ~34.36 psu and temperature ~4.44 °C (Fig. 5, green dots). AAIW with intermediate properties is produced by mixing between these two varieties in the SAZ (yellow dots). A homogeneous pool of AAIW with southern source characteristics (salinity~34.34 psu, temperature~4.4 °C) is found inside the anticyclonic feature west of the South Tasman Rise.

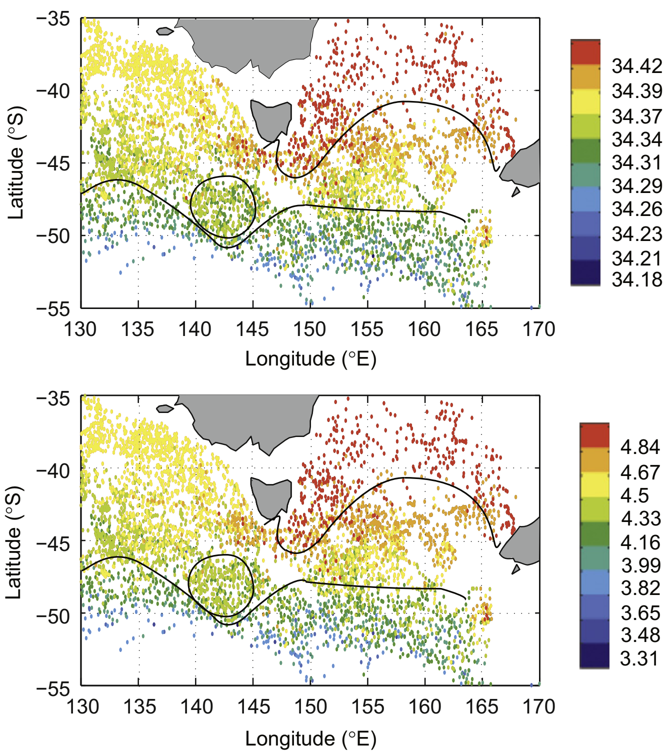

Fig. 5. AAIW salinity (top) and temperature (bottom) at γ^n=27.4 kg m^{-3}. Black lines mark the limit for the two AAIW sources. The position of the anticyclonic eddy on the west of the South Tasman Rise is indicated by an ellipse.

On the eastern side of Tasmania interleaving is enhanced where the warm, salty northern and, cold, fresh southern varieties of AAIW meet. This area is located between 43–48°S and 151–160°E. Fig. 6 shows the θ–S curves from the two hydrographic sections. At SR3, the θ–S profiles from the SAZ form a tight cluster (black curves, Fig. 6, left), with relatively little evidence of interleaving with profiles to the north and south. This is explained by the presence of the permanent anticyclonic recirculation, which appears to inhibit exchange with surrounding waters. At P11S, θ–S curves from the SAZ fall in two clusters (Fig. 6, right; black solid and dash lines) resulting from interleaving with waters north and south of the SAZ.

3.4. Subsurface salinity maximum

Vertical sections of salinity in the upper 500 dbar of the water column show stronger southward advection of warmer, saltier waters at subsurface depths in the east than in the west. As we mentioned at the start of Section 3, the EAC can be seen in the zonal leg of the P11S section, as a relatively warm, salty wedge between 149°E and 151°E (Fig. 2A–C). For the meridional P11S section, water with salinity higher than 34.7 psu can be seen spreading as far south as 50°S, with some isolated patches at 100–200 dbar below the surface (Fig. 2B, upper right panel, grey filled contours). The depth of these warm, salty patches increases as they move southward. Isolated warm and salty subsurface patches are also seen at the SR3 section, although there is no continuous connection with waters north of the STF as we see at P11S.

Monthly mean salinity sections from the CSIRO climatological Atlas for Regional Seas (CARS2006a) (Ridgway et al., 2002) at 140°E and 150°E show the seasonal evolution of this intrusion (Fig. 7A and B, respectively). On the western side, at 140°E (Fig. 7A), the limit between the STF and the SAZ waters is more clearly defined during winter, with a very well developed winter

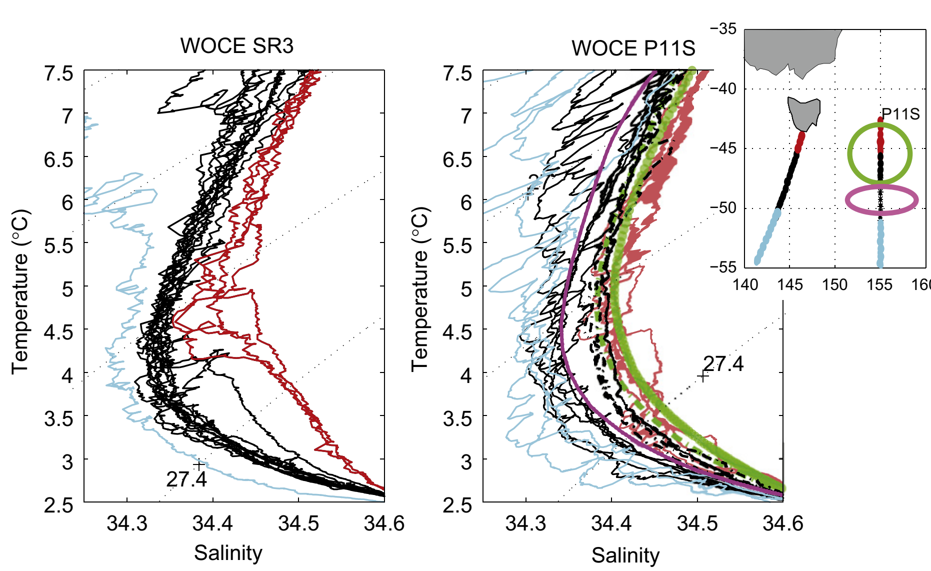

Fig. 6. Potential temperature/salinity (θ–S) curves for SR3 and P11S stations from 43°S to 51°S. Black dotted lines are potential density contours. Stations belonging to the STF area of influence are in red, north of ~46°S. Stations within the SAZ are in black and waters in the SAF area are in blue, ~50°S. The mean θ–S properties on the east of Tasmania (green and magenta–purple) are compared to stations from P11S (right). Stations represented by black stars in the map correspond to black lines at P11S θ–S curves.

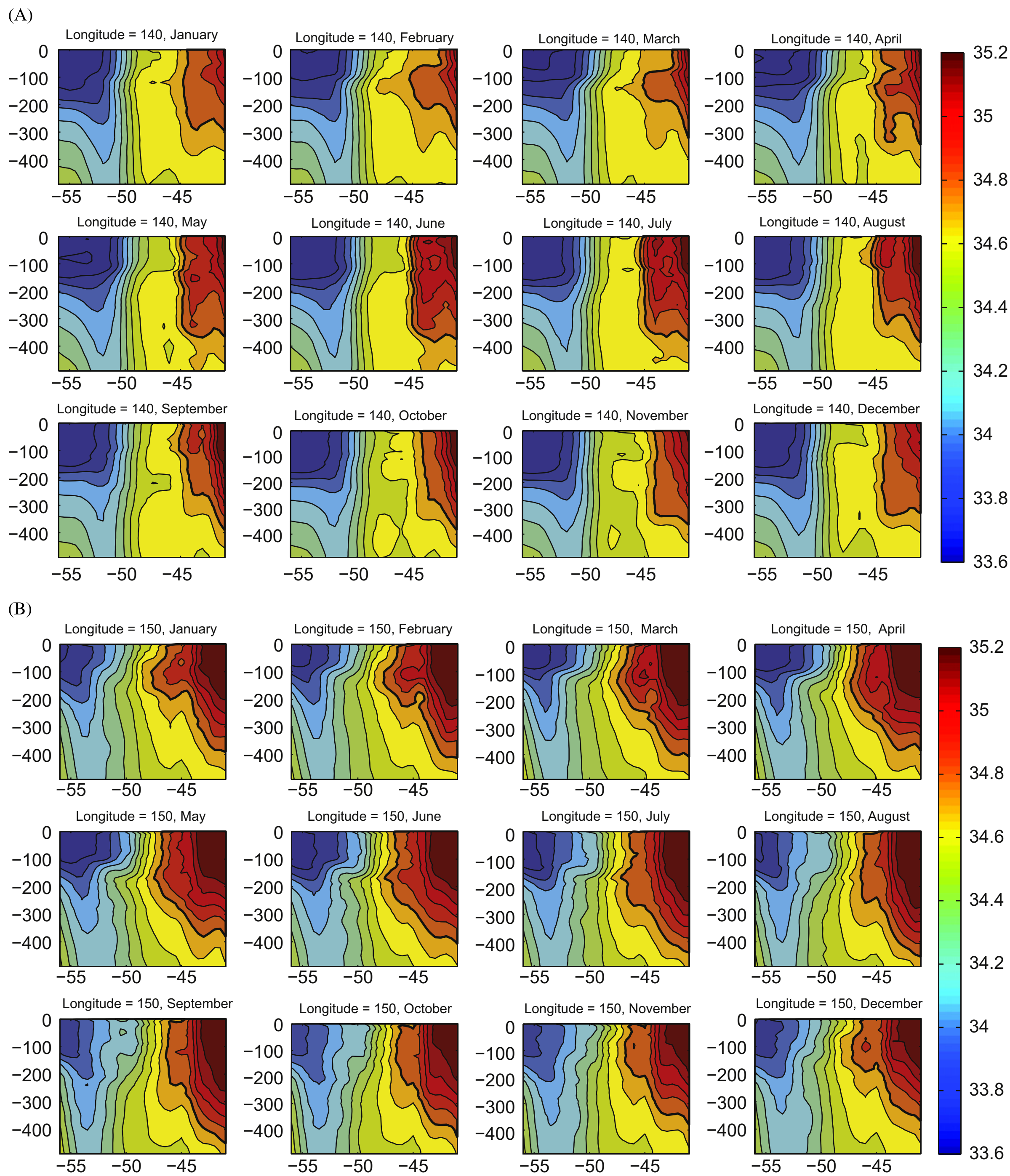

Fig. 7. Monthly mean salinity section at 140°E (A) and 150°E (B) between 40°S and 56°S from January to December taken from CSIRO Climatological Atlas for Regional Seas (CARS2006a). The black bold line indicates the 34.7 psu isohaline.

mixed layer. In January, an intrusion of warm and salty water starts to develop south of the STF (∼45°S) at around 150 dbar. It gets stronger during February and weakens during March. On the eastern side, at 150°E (Fig. 7B), the influence of subtropical waters is remarkable. The subsurface intrusion advection of warm, salty waters into the SAZ is present all year round. During January, a plume of salinity higher than 34.7 psu (at ∼100 dbar) starts to develop south of 45°S. The core of the plume gets saltier during January and February reaching values higher than 35 psu that can detach from the main inflow and form similar patches or 'eddies' between 100 and 200 dbar as seen at P11S (Fig. 2B, upper right panel). From May to September, winter convection occurs, mixing these salty waters with the water below throughout the winter. The presence of the strong subsurface salinity maximum, hence stronger stratification, in the east could reduce the effectiveness of winter convection, resulting in a thinner and less homogeneous SAMW layer.

The larger contrast in temperature/salinity between north and south of the STF and the slower circulation in the eastern SAZ allows a stronger subsurface salinity-maximum to develop in the east. In summer, surface waters warm and become less dense on both sides of the STF (Fig. 2A and C). With temperature and density being stratified as a result of the summer mixed layer formation, strong southward diffusion and advection of salinity along isopycnals are possible at the base of the mixed layer, forming a subsurface salinity maximum (Fig. 2B).

The advection of subsurface salinity during summer is likely to supply micronutrients, especially iron, into the SAZ south of Tasmania. Subtropical waters in the region are generally replete with micronutrients and are mainly limited by major nutrient supply (N, P, and Si) (Ellwood et al., 2008). In the same area and depth range as the subsurface salinity maximum is found (approximately between 100 and 200 m), elevated dissolved and particulate iron concentrations have been documented (Bowie et al., 2009). In winter, deep convection would transport this iron into the surface layer, perhaps contributing to higher biomass observed in the east. In addition, Kahru et al. (2007) reported how cross–frontal eddy activity in the Southern Antarctic Circumpolar Current Front enhanced conditions for phytoplankton biomass growth. Following the Kahru et al. (2007) interpretation, the mesoscale features associated with the EAC retroflection along ~45°S could be a mechanism to bring those micronutrients from the subsurface 'eddies' via upwelling back to the photic zone. The upwelled nutrients can be used by the phytoplankton and maintain the high biomass seen in this region.

4. Argo float trajectories

Water mass properties show a contrast between the eastern and western SAZ, south of Tasmania. The Montgomery streamfunction distribution and previous discussion suggest the E–W contrast is maintained by the regional circulation. We now use Argo float trajectories to reveal the regional circulation in greater detail and explore its connection to the distribution of water properties.

The trajectories of 48 Argo floats passing through the region tend to follow one of four distinct circulation pathways (Fig. 8). Routes 1 and 2 represent 22% and 31%, respectively, of the total Argo float trajectories. Route 1 shows a westward flow south of Tasmania, between the continental shelf and the South Tasman Rise (STR) (Fig. 8, top left). It is followed by floats with very different origins: from the north, following the path of the EAC; and from the eastern SAZ. Route 2 (Fig. 8, top right) represents a northwestward flow and a deep-reaching anticyclonic recirculation between 47–49°S and 140–145°E, described by Rintoul and Sokolov (2001), just west of the STR. The presence of this anticyclonic recirculation enhances the contrast between SAMW/AAIW properties to the east and west of Tasmania, as discussed in Sections 3.2 and 3.3. Bathymetry, in particular the STR, also exerts a strong influence on the characteristics of the main flows in the region. Route 1 passes through the gap between the Tasmanian continental slope and the STR. Floats approaching the STR from the west are blocked by the STR and turn back to the northwest toward the Great Australian Bight. No floats were observed to pass from the western SAZ to the eastern SAZ north of the southern limit of the STR.

East of Tasmania, Argo float trajectories are more variable in the SAZ. Routes 3 and 4 correspond to 18% and 15%, respectively, of the total float trajectories. Route 3 (Fig. 8, lower left) depicts a sluggish circulation mainly in the SAZ region between 150°E and 160°E and close to Tasmania. Route 3 also depicts trajectories moving back and forth across 44°S, probably associated with mesoscale features as the EAC extension turns back to the northeast. A northward flow can be inferred from the slope of the isopycnals on the offshore end of the short zonal portion of P11S (Fig. 2C). Route 4 (Fig. 8, lower right) is characterized by a slow northeastward flow in which the floats seem to be travelling in the same direction as the deflection to the east of the EAC between ~33°S and 44°S (east of 160°E), and so these floats are more likely to be influenced by the EAC variability. Rintoul and Sokolov (2001) also described a recirculation in the east, extending northward to ~40°S and then flowing westward. This recirculation shows characteristics of Routes 1 and 3: waters from the eastern SAZ move northward and can get trapped in the flow southward along the Tasmanian coast to enter the west south of Tasmania. About 14% of the floats followed other trajectories not described here.

Properties of the February mixed layer and on the 27.2–γ^n surface (mean depth of ~1100 m) both reflect the large influence of the regional circulation in establishing the contrast between properties of the upper ocean between east and west of Tasmania (Fig. 9). In the east, the sluggish circulation in the SAZ and the strong

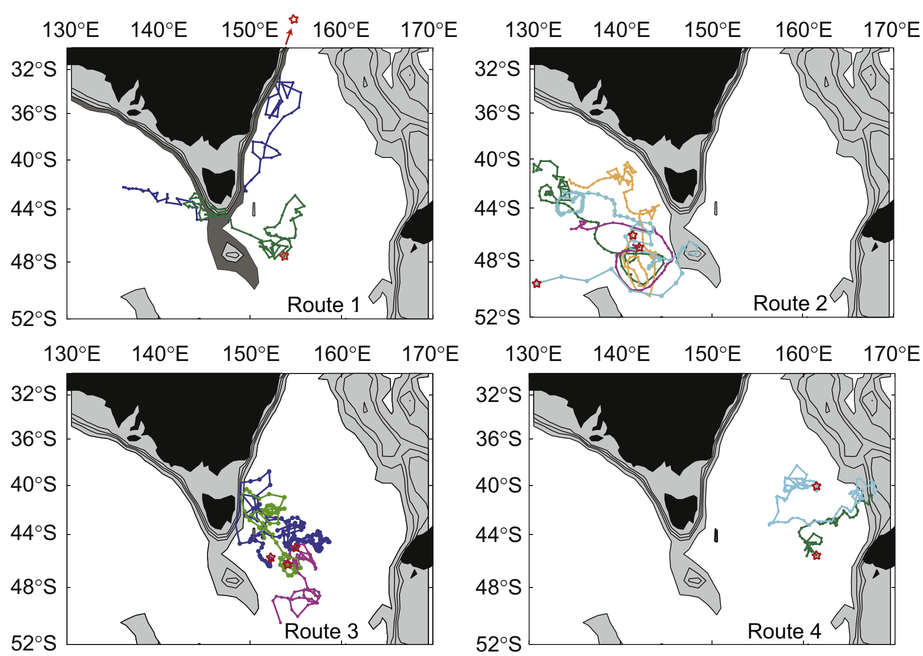

Fig. 8. Routes of the main regional circulation described by the Argo float trajectories. Each colour represents a float. The start of each trajectory is signed by a red star. The Wmo number for each float is: R1: 5900873 (blue), 5900457 (green); R2: 7900117 (purple), 5900849 (orange), 5900841 (green), 5900689 (blue); R3: 5900452 (blue), 59001188 (green), 5901327 (purple); and R4: 5900601 (light blue), 5901270 (green). Bathymetry higher than 2000 m is shown (shaded).

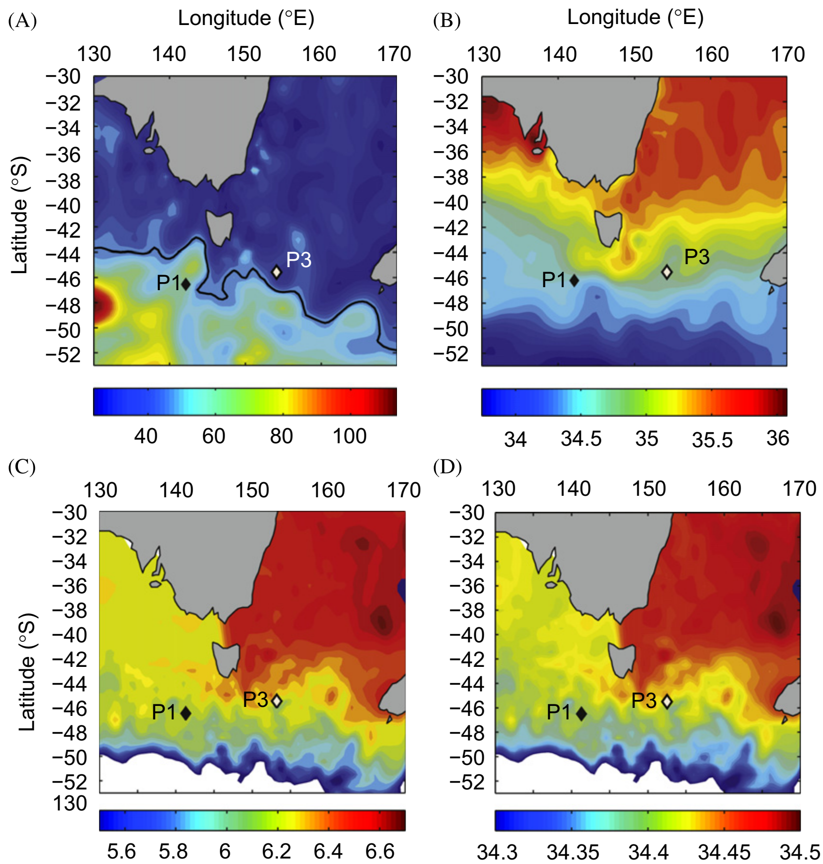

Fig. 9. February mixed layer depth and salinity (A, B). The mixed layer depth has been calculated using a density difference criterion with a threshold of 0.03 kg m^{-3}. The 50–55 m mixed layer depth is depicted by the black contour line. Temperature and salinity at a neutral density surface of 27.2 kg m^{-3} (mean depth of 1100 m) (C, D). Process stations 1 and 3 are also shown.

input of warm, salty waters from the Tasman Sea at different depths promote a strong meridional temperature and salinity gradient (Fig. 9B–D). A warm and salty wedge of subtropical water east of Tasmania is carried southward by the EAC Extension (Fig. 9B). The Tasman Outflow flows westward as a warm and salty filament just south of Tasmania (Fig. 9C and D), following Route 1 (Fig. 8, top left). The temperature and salinity signature of the Tasman Outflow can be traced as far as 135°E before it mixes with the surrounding waters.

The mixed layer depth shows a zonal contrast between the east and west of Tasmania (Fig. 9A). Mixed layer depths deeper than 50 m are found southwest of Tasmania, with a weak meridional gradient in mixed layer depth south of 44°S. Southeast of Tasmania, mixed layer depths shallower than 50 m extend further south than in the west. A similar behaviour is found in the salinity distribution of the mixed layer (Fig. 9B). West of Tasmania, salinity of the mixed layer shows little contrast between the northern and southern SAZ boundaries. In contrast, the enhanced southward spreading of subtropical water in the east creates a strong meridional salinity gradient in the eastern SAZ. A similar pattern is found on the 27.2–γ^n surface.

The Tasman Outflow carries older, lower oxygen SAMW and AAIW from the east to west through the South Tasman Saddle (Rintoul and Bullister, 1999; Rintoul and Sokolov, 2001). Oxygen concentrations of SAMW are lower between 43°S and 7°S on the zonal leg of P11S section compared to the SAMW found on the SR3 and the southernmost SAZ stations at P11S (not shown). As a result, the intermediate waters to the east of Tasmania include both older and poorly ventilated, waters entering the region from the north, and younger waters entering from the south (for SAMW) formed locally. The weak circulation regime east of Tasmania is confined: in the east by the continental shelf west of New Zealand; in the north, by a strong contrast in *T–S* with subtropical waters moving southward from the Tasman Sea; and in the west, by the South Tasman Rise (Fig. 4). Water exits this region either eastward, with the SAF, or northwestward through the South Tasman Saddle (Route 1, Fig. 8).

5. Summary

The water properties of the SAZ south of Tasmania show strong contrasts between east and west sectors. These property contrasts likely contribute to the biological and biogeochemical differences observed east and west of Tasmania, the main focus of the SAZ-Sense experiment.

Analysis of WOCE hydrography, Argo float profiles and trajectories, and high resolution climatology reveals the main features of the regional circulation. Warm, salty subtropical waters are carried into the eastern SAZ, south of Tasmania, by the EAC. At intermediate depths, the Tasman Outflow allows relatively warm and salty water from the east of Tasmania to enter the western region. This flow, connecting the Pacific and Indian subtropical gyres south of Australia, is part of a southern hemisphere 'super-gyre' connecting the basins (Ridgway and Dunn, 2007). Speich et al. (2002) showed that this flow path contributes to the global overturning circulation. The STR divides the regional circulation into two regimes with strong contrasts in water properties. The circulation in the east shows a weak geostrophic flow and enhanced subtropical input by EAC warm core eddies, intrusions and a subsurface southward advection of salinity. Close to Tasmania, Argo float trajectories show that the STF is crossed back and forth, probably associated with strong mesoscale eddies of the EAC. Intrusions or interleaving are very important in this region because they promote strong isopycnal and diapycnal mixing between subtropical and subantarctic waters. The influence of the subsurface southward advection of salinity is higher in the east than in the west. While in the east it is a well-established event, in the west, it seems to depend on the seasonal strength of the EAC extension that reaches the western SAZ waters in the form of eddies. The regional circulation in the west is governed by a northwestward circulation with little apparent flow to the east across the STR. Immersed in the mean flow, a deep-reaching anticyclonic recirculation is located just west of the STR (47–49°S and 140–145°E).

These regional circulation and mixing processes therefore drive the strong contrasts in water properties in the eastern and western SAZ discussed here and by previous authors (e.g. McCartney, 1977; Rintoul and Bullister, 1999; Sokolov and Rintoul, 2002). Southern Ocean waters exert a strong influence over the western SAZ, resulting in relatively cold and fresh waters compared to the warm and salty waters in the east. Two local varieties of SAMW and AAIW have been found inside the permanent anticyclonic recirculation west of the STR. The thickest SAMW is found here, suggesting the deep isopycnal bowl, associated with the anticyclonic flow, preconditions the region for deep winter convection. θ–S relationships around Tasmania reveal the confluence of AAIW with two very distinct origins, a warmer and saltier AAIW formed in the eastern South Pacific Ocean and a colder, fresher and better ventilated AAIW formed in the western South Atlantic Ocean. The latter water mass is advected eastward by the ACC and is found prominently on the west, just north of the SAF. AAIW of intermediate θ–S properties are found in the east where interleaving is very strong and the circulation is very weak.

The enhanced input of subtropical water and shallower mixed layer depth in the east supports the higher biomass observed here. North of the STF, waters are replete with micronutrients, including iron, and are mainly limited by major nutrient supply (N, P, and Si). The distribution of micronutrients in the SAZ varies from north to south (Bowie et al., 2009; Lannuzel et al., 2011): higher iron concentrations are found in the northern edge of the SAZ (compared to the south), particularly to the southeast of Tasmania. The SAF is low in Fe and in Si, and relatively high in P and N. The high biomass region in the eastern SAZ is also affected by numerous EAC eddies that deliver higher dissolved iron concentrations from northern subtropical waters and enhance phytoplankton growth (Mongin et al., 2011).

Tasmanian and SAZ marine ecosystem changes are expected to be larger in the eastern SAZ than on the western side of the SAZ south of Australia (Hill et al., 2008). Our results suggest that intensification of the EAC extension would strongly affect the marine ecosystems of the eastern SAZ, as the region becomes more subtropical. As a result, the input of micronutrients, especially iron, to the macronutrient rich waters of the Southern Ocean could increase. Higher salinity intrusion is also likely to occur, intensifying the contrast between the northeast and the southeast SAZ. Such intrusions would also likely affect the depth of the mixed layer, intensifying the stratification and hence, forming shallower mixed layers. The southward expansion of subtropical waters has been linked to ecosystem changes near the coast of Tasmania, where kelp forest has declined and been replaced by sea urchin barrens, with impacts on the abalone and crayfish fisheries (Ling et al., 2008). Our results suggest a southward expansion of subtropical waters might also have had an impact on ecosystems in the eastern SAZ, where the influence of subtropical waters is larger. Strategies for the sustainable management of marine resources will need to take into account changes in regional circulation driven by climate change and natural variability (Poloczanska et al., 2007).

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