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Analysis of hydrographic and stable isotope data to determine water masses, circulation, and mixing in the eastern Great Australian Bight

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[1] Hydrographic and stable isotope data from waters in the eastern Great Australian Bight (GAB) sampled during March–April 1998 indicate that both mixing and evaporative processes are important on the shelf. Five water masses are defined on the basis of their temperature, salinity, $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values. Two of these are end-members, the Flinders Current (FC) and the Great Australian Bight Plume (GABP), whereas the other three are a result of mixing between these two end-members. Water mass distribution reflects an anticyclonic gyre in the eastern GAB. Cool and fresh water present at depth along the Eyre Peninsula is sourced from upwelling of Flinders Current water directly from the shelf break. This water is progressively heated, evaporated, and mixed with warmer and more saline shelf waters as it flows around the gyre. High temperatures, salinities, and $\delta^2\text{H}$ values in surface waters in the central GAB suggest that the Great Australian Bight Plume has a greater spatial extent than previously recorded, also occurring along the shelf edge between 130°E and 133°E . A high temperature, high salinity, low $\delta^2\text{H}$ water mass that is isotopically similar to the Flinders Current occurs in the west of the study area, indicating intrusion of Flinders Current water into the central GAB. Differences in isotopic compositions of off-shelf water suggest that the Great Australian Bight Plume is flowing off the shelf and mixing with Flinders Current water at $\sim 132^\circ\text{E}$; however, this outflow does not generate an eastward flowing current during the period when samples were collected.

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1. Introduction

[2] The eastern Great Australian Bight (GAB) is part of an extensive zonal, midlatitude shelf which hosts one of the world's largest cool-water carbonate provinces. It is also an area of seasonal upwelling of the world's only northern boundary current, the Flinders Current (FC), which supplies nutrients to a generally oligotrophic shelf. The highest levels of primary and secondary productivity in Australian waters have been recorded in the eastern GAB during periods of upwelling, and the area supports several major commercial fisheries [Ward *et al.*, 2006]. Benthic biological production has been linked to oceanography in the GAB [James *et al.*, 2001]; therefore an understanding of regional oceanographic processes is important for both cool-water carbonate sedimentation and the pelagic shelf ecosystem in an important fisheries area [Kämpf *et al.*, 2004; Ward *et al.*, 2006].

[3] Despite its importance, the eastern GAB has not been studied extensively. Most research has focused on sea surface temperature satellite imagery [Griffin *et al.*, 1997; Herzfeld, 1997; Herzfeld and Tomczak, 1999] and modeling of the physical oceanography [Middleton and Platov, 2003; Cirano and Middleton, 2004; McClatchie *et al.*, 2006]. The minimal hydrographic data published has focused on upwelling events and not general shelf circulation [Kämpf *et al.*, 2004; Ward *et al.*, 2006]. In addition, no previous work has been published on stable isotopes of the waters in the GAB. Oxygen and hydrogen isotopes in seawater can provide important information as to the origins, mixing patterns and levels of air-sea interaction of different water masses [Lloyd, 1966; Gat *et al.*, 1996; Frew *et al.*, 2000], and can be used with hydrographic proxies to give a more robust understanding of the regional oceanography.

[4] The oxygen and hydrogen isotopic compositions of seawater ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) are affected by a combination of evaporation, precipitation and physical mixing between water masses [Epstein and Mayeda, 1953; Friedman, 1953; Craig and Gordon, 1965; Corlis *et al.*, 2003]. $\delta^{18}\text{O}$ is the ^{18}O to ^{16}O ratio and $\delta^2\text{H}$ is the ^2H to ^1H ratio relative to Vienna Standard Mean Ocean Water (VSMOW). The heavy isotopes of oxygen and hydrogen can be enriched relative to VSMOW by fractionation and loss of the light isotope

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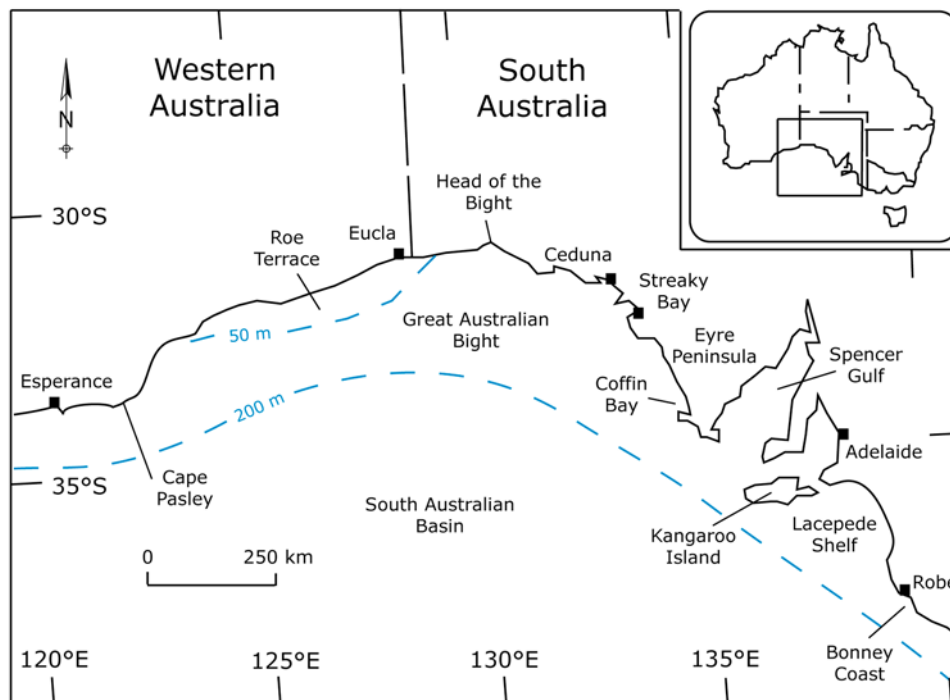


Figure 1. Map showing the Great Australian Bight (GAB) study area. Dashed lines represent bathymetric features of the shelf edge and Roe Terrace. Locations and features mentioned in the text are marked.

during evaporation, and depleted by addition of fresh water from precipitation, sea-ice melt and continental runoff [Epstein and Mayeda, 1953; Gat et al., 1996; Horita et al., 2008; Meredith et al., 2008]. Once a water mass is isolated from the surface ocean it is no longer affected by these processes and its isotopic composition can be used as a tracer for conservative mixing [Frew et al., 2000].

[5] The purpose of this research is to determine water mass characteristics and circulation on the eastern GAB shelf and give insight into the interaction between on-shelf and off-shelf waters in a regional context. Hydrographic data from CTD profiles are used in conjunction with oxygen and hydrogen isotopes to understand circulation, mixing and evaporation processes occurring on the shelf.

1.1. Setting

[6] The GAB is an extensive geomorphic feature along the southern margin of Australia, covering 35% of the southern shelf with an area of 177,130 km² [James and von der Borch, 1991]. It extends from Cape Pasley in the west to the southern tip of the Eyre Peninsula in the east (Figure 1). Most of the shelf has depths between 50 and 120 m with the shelf break at approximately 200 m water depth.

[7] The GAB has a Mediterranean-like climate with hot dry summers and cool wet winters [Longhurst, 1998]. Mean annual rainfall and evaporation for Streaky Bay is 375 mm and 2100 mm, respectively [Government of SA, 2007], with mean monthly maximum temperatures ranging from 29°C in January to 16.5°C in July [Bureau of Meteorology, 2008]. From November to March, Southern Australia experiences a succession of slow-moving high pressure systems that move east across the GAB. These weather systems create south-

easterly winds in the eastern GAB that are conducive to upwelling. Every few summers, intense cyclonic depressions originating in northern Australia can bring heavy rainfall to the area [Edyvane, 1998; James et al., 2001]. There are no significant rivers in the GAB and therefore no input of surface fresh water, terrestrial nutrients or siliciclastic sediments.

1.2. Oceanography

[8] The oceanography of the eastern GAB is seasonal, with a well-mixed water mass in winter and stratification and spatial temperature and salinity variation in summer. Understanding of the shelf circulation has come predominantly from modeling studies [Herzfeld, 1997; Herzfeld and Tomczak, 1999; Middleton and Platov, 2003; Cirano and Middleton, 2004]. Herzfeld [1997] modeled general shelf circulation in the eastern GAB throughout the year. During May to early October, GAB waters are well mixed and have a constant temperature throughout. The Leeuwin Current (LC; Figure 2) flows into the GAB during this time and forms an isothermal water mass on the shelf. Waters are around 17°C throughout [James et al., 2001]. Downwelling is prominent in winter, as saline shelf waters formed over summer cool and flow off the shelf, and the shelf-edge LC acts as a barrier to Southern Ocean water intruding onto the shelf [Longhurst, 1998; James et al., 2001].

[9] During summer, a spatial gradient develops across the shelf, with intense surface heating and evaporation in the northwest and localized upwelling of cool Southern Ocean water in the east [Herzfeld, 1997]. The Great Australian Bight Plume (GABP) forms from intense surface heating and evaporation over the shallow Roe Terrace in summer (Figure 2). It is characterized by salinities generally exceed-

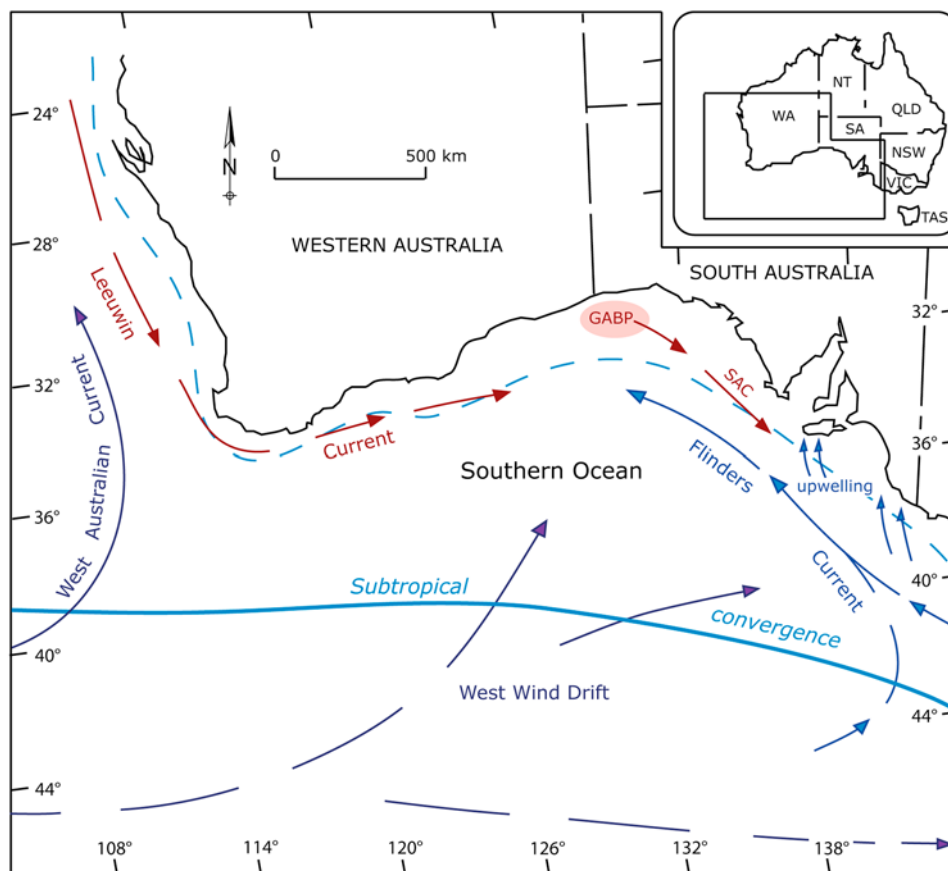


Figure 2. Oceanography of the southern Australian region, showing the major currents present in the study area. GABP is Great Australian Bight Plume; SAC is South Australian Current; dashed line is shelf edge.

ing 36.0 [Herzfeld, 1997] and sea surface temperatures up to 23°C [James et al., 2001]. Waters also become stratified from surface heating and intrusion of Southern Ocean water onto the shelf, with a seasonal thermocline observed between 50 and 70 m [Middleton and Platov, 2003]. Upwelling of cool, nutrient-rich water along the coast of the southern Eyre Peninsula during late summer–early autumn leads to local enhanced levels of primary productivity and increases in zooplankton biomass [Ward et al., 2006]. Previous research attributes the source of this upwelled water to deep upwelling off Kangaroo Island rather than from the GAB shelf break [Kämpf et al., 2004; McClatchie et al., 2006]. Upwelling events along the Eyre Peninsula occur on average two to three times during the austral summer [Kämpf et al., 2004].

[10] The FC is a northern boundary current that flows west along the continental slope of southern Australia [Figure 2; Bye, 1972; Middleton and Cirano, 2002]. It is sourced from the Subantarctic Zone, where Subantarctic Mode Water and Antarctic Intermediate Water flow north across the subtropical front and then west along the Australian continental slope, forming the FC [McCartney and Donohue, 2007]. The FC is also fed by the Tasman Outflow which is a remnant of the East Australian Current that sinks and flows westward around the southern tip of Tasmania [Rintoul and Sokolov, 2001; Speich et al., 2002; Cirano and Middleton, 2004]. The FC has been described using current meter data [Hufford et al., 1997] and modeling studies

[Middleton and Cirano, 2002] and appears to be defined by westward flow. Its hydrographic properties have not been documented. It flows beneath the LC during winter [Middleton and Cirano, 2002], but during summer it is not known if the FC is present as a shallower current.

2. Analytical Techniques

[11] Water samples were collected from 57 stations on a research cruise from Robe (~140°E) to the central GAB (~131°E) on the RV *Franklin* from 19 March to 7 April 1998 (Figure 3). This sampling period is during late austral summer–early autumn. Stations 17–52 in the eastern GAB are the focus of this study. Stations 7–16 from around Kangaroo Island and the Bonney Coast are also used herein to compare water mass characteristics of this region with eastern GAB samples. Temperature, salinity and dissolved oxygen data were collected using a Neil Brown Instrument Systems MkIII B Conductivity Temperature Depth (CTD) profiler on the *Franklin*. Nitrate and phosphate contents were measured using an Alpkem Flow Solution system on board from water samples collected in Niskin bottles at various depths during CTD casts. The detection limits for nitrate + nitrite and phosphate were 0.02 $\mu\text{mol/L}$ and 0.007 $\mu\text{mol/L}$, respectively, calculated as three times the standard deviation of the blank. Water samples were then refrigerated until analyzed for stable isotopes. Hydrographic

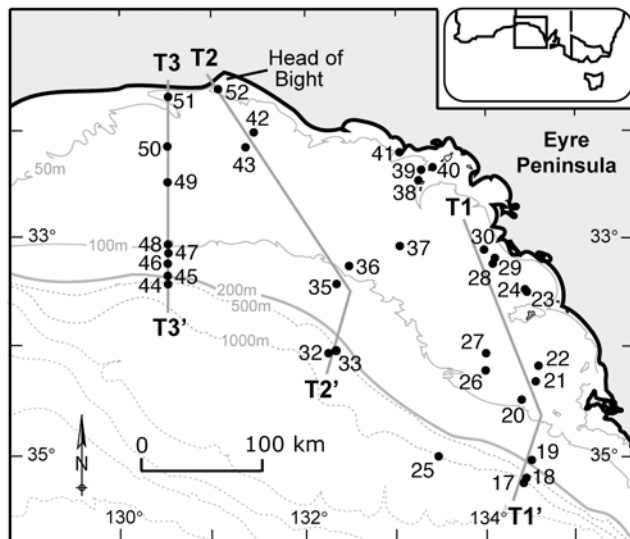


Figure 3. Map of the eastern GAB showing locations of the sampling stations used in this study. Also shown are the locations of transect lines presented in Figures 6 and 12. T1 is eastern transect, T2 is central transect, and T3 is western transect.

data are available from the Australian Commonwealth Scientific and Research Organization (CSIRO) Data Trawler database [CSIRO, 2001].

[12] One hundred samples from stations 17–52 were analyzed for oxygen and hydrogen isotope ratios at the Queen’s Facility for Isotope Research. Oxygen isotopes were measured in December 1998 using the standard $\text{CO}_2\text{-H}_2\text{O}$ isotope equilibration method of *Epstein and Mayeda* [1953]. The method was slightly modified by using ethanol dry ice to freeze the water and equilibrating samples in a shaking water bath overnight at 25°C . Hydrogen isotopes were measured in April 2008 on a Finnigan MAT 252 mass spectrometer connected to an automated Finnigan HDevice. Water samples were sent through a heated glass column with chrome metal to remove the oxygen and allow the H_2 gas to enter the mass spectrometer. Measurements of the $^2\text{H}/^1\text{H}$ and $^{18}\text{O}/^{16}\text{O}$ ratios are presented in standard “ δ ” notation with respect to VSMOW. The δ value is defined as:

$$\delta(\text{per mil}) = (R/R_{\text{VSMOW}} - 1) \times 10^3$$

where R is the isotope ratio $^2\text{H}/^1\text{H}$ or $^{18}\text{O}/^{16}\text{O}$. Reproducibilities of the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ measurements are ± 1.0 per mil and ± 0.3 per mil, respectively.

3. Results

3.1. Hydrographic Data

[13] We first used hydrographic data to identify different water masses. Three major water masses were identified in the study region on the basis of their temperatures and salinities (Table 1). The FC has temperatures and salinities of $<15^\circ\text{C}$ and <35.5 , respectively (Figure 4), and is present in off-shelf stations below the seasonal thermocline as well as on the shelf at depth along the Eyre Peninsula

between Coffin Bay and Streaky Bay (Figure 1). A mixed water mass with intermediate temperatures and salinities is present at the surface along the coast and at depth in the central part of the study area. This mixed water mass increases in temperature and salinity from east to west and can be divided into two water masses, mixed (a) and mixed (b), on the basis of temperature, salinity and spatial distribution (Figure 4). The GABP has temperatures and salinities as high as 21°C and 36.2 , respectively, and is present on the mid shelf and along the shelf edge in the western and central parts of the study area.

[14] Temperatures and salinities of FC water remain relatively constant within the top 200 m, indicating upwelling from this depth onto the shelf (Figures 5a and 5b). Depth appears to influence nitrate contents of waters, however, with the majority of nitrate values $\sim 2 \mu\text{mol/L}$ within the top 120 m (Figure 5c). Several samples of FC waters on the shelf show nitrate enrichment, which match nitrate values present off the shelf at ~ 200 m depth. Water from a shelf station adjacent to Kangaroo Island east of the GAB (KI Station 16) has a higher nitrate content than any GAB shelf waters. Dissolved oxygen contents vary widely on the shelf, with highest values found in FC waters and lowest values found predominantly in GABP waters (Figure 5d). Dissolved oxygen is relatively constant below 250 m depth. The high dissolved oxygen content of $\sim 250 \mu\text{mol/L}$ matches reported values of Subantarctic Mode Water [McCartney, 1977].

[15] There is an east to west variation in hydrographic properties of shelf waters. CTD profiles of representative stations from eastern, central and western transects (Figure 3) show that eastern waters have lower temperatures and salinities and higher dissolved oxygen contents than waters in the central and western parts of the study area (Figure 6). Stations 21, 22, 23 and 24 are upwelling areas along the Eyre Peninsula, with FC water below the seasonal thermocline and Mixed water above. Temperatures and salinities of bottom waters at stations 21 and 22 are the lowest of all shelf stations, and stations 23 and 24 have the shallowest seasonal thermo-

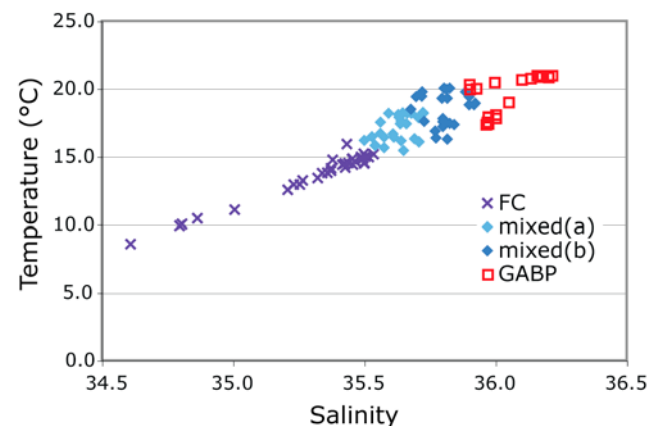


Figure 4. Temperature-salinity plot of samples divided into three water masses on the basis of temperature and salinity: Flinders Current (FC), Mixed waters, and Great Australian Bight Plume (GABP). Mixed waters are divided into mixed (a) and mixed (b).

Table 1. Properties of Water Masses Defined on the Basis of Temperature and Salinity Measured in March 1998

Water Mass	Temperature (°C)	Salinity	Density (kg/m ³)	Oxygen (μmol/L)	Nitrate (μmol/L)	Phosphate (μmol/L)
Flinders Current	<15.2	<35.5	26.0–26.5	206–317	1.3–19.1	0.3–1.3
Mixed water	15.4–20.0	35.5–35.9	25.5–26.0	172–288	0–3.2	0–0.5
GAB Plume	17.4–21.0	35.9–36.2	25.0–25.5	150–240	0–2.5	0–0.7

cline (<20 m). Stations from the central (stations 35 and 36) and western (stations 48 and 49) parts of the study area show a well-mixed layer of GABP water down to ~60 m, with much higher temperatures and salinities than stations 21 and 22. Stations 35 and 36 have lower temperatures and salinities than stations 48 and 49, however properties of all four stations converge at depth. There is a substantial dissolved oxygen maximum for waters at 40–50 m depth in stations 21 and 22 (Figure 6c) and a less pronounced maximum in stations 35, 36, 48 and 49 at greater depths. The dissolved oxygen maximum correlates with the bottom of the seasonal thermocline at each station. These temperature, salinity and dissolved oxygen profiles highlight how distinctly different the eastern stations are from the central and western stations.

[16] Temperature and salinity profiles of off-shelf stations show a surface mixed layer down to ~70 m and a gradual decrease in temperature and salinity with depth below the seasonal thermocline (Figure 7). In comparison, data from Kangaroo Island and the Bonney Coast (KI-BC), an area east of the GAB (137–140°E), show upwelling from ~250 m. Water characteristics of this area are distinctly different from waters in the eastern GAB. Upwelled waters at depth along

the western Eyre Peninsula have a similar temperature-salinity relationship to waters from off-shelf stations in the eastern GAB (Figure 7c) and are not associated with upwelling data from Kangaroo Island and the Bonney Coast.

3.2. Stable Isotope Data

[17] We now use stable isotope data to refine and modify the water mass categories identified in the previous section. $\delta^{18}\text{O}$ and $\delta^2\text{H}$ relationships in waters of the eastern GAB are variable and indicate mixing of waters with different isotopic compositions (Figure 8). The $\delta^{18}\text{O}$ values of waters range from +0.4 to +2.1 per mil and $\delta^2\text{H}$ values range from -3.5 to 7.0 per mil. $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of waters vary widely across the shelf, with differences between adjacent sites of up to 0.9 per mil and 5.5 per mil for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively, reflecting a poorly mixed system. The three major water masses defined on the basis of temperatures and salinities are not isotopically distinct (Figure 8), but the water masses can be refined on the basis of their $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values. There is an increase in $\delta^2\text{H}$ values between FC and Mixed waters, however $\delta^2\text{H}$ values of GABP waters vary widely, from -2.5 to +7 per mil. GABP waters with $\delta^2\text{H}$ values <3 per mil were

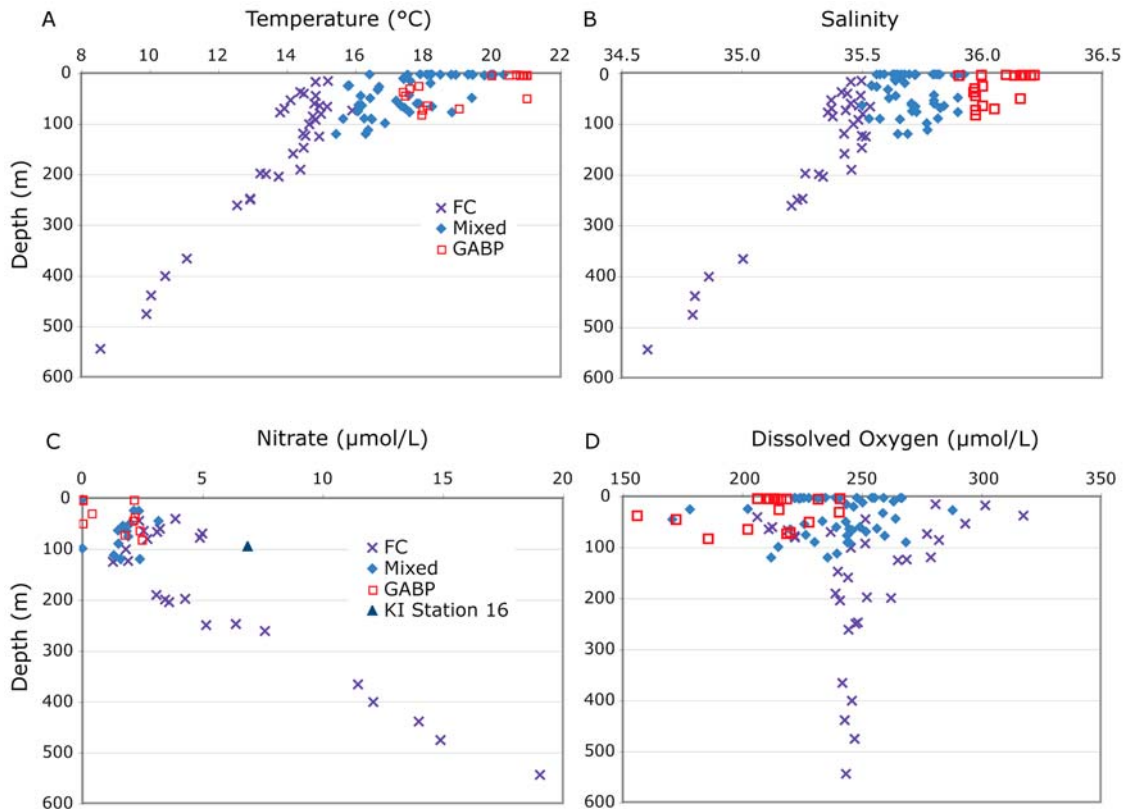


Figure 5. Properties of each water mass defined on the basis of temperature and salinity, showing depth profiles of (a) temperature, (b) salinity, (c) nitrate, and (d) dissolved oxygen from stations shown in Figure 3. “KI station 16” in Figure 5c is a station on the shelf close to Kangaroo Island (Figure 1).

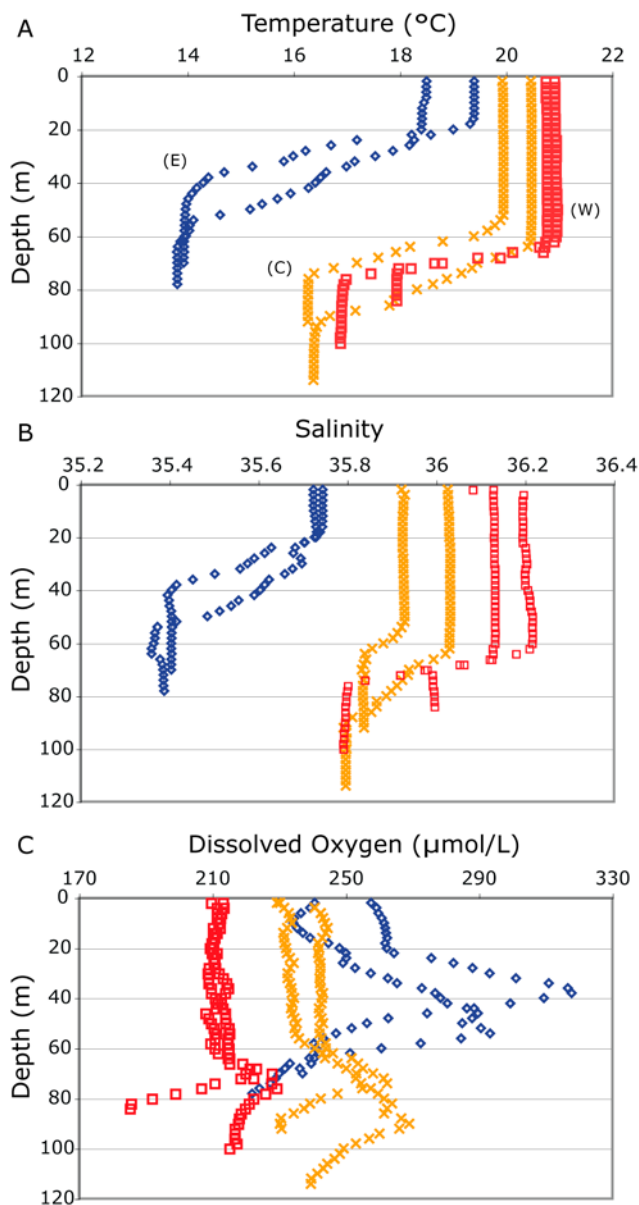


Figure 6. CTD profiles of (a) temperature, (b) salinity, and (c) dissolved oxygen of stations 21–22 from the eastern region (E; \diamond), 35–36 from the central region (C; \times) and 48–49 from the western region (W; \square) of the study area (Figure 3).

defined as a separate water mass, which has a similar isotopic composition to off-shelf FC waters but has much higher temperatures and salinities. This water is modified FC water (FC(a)) and is present on the shelf in the west of the study area. In addition, several samples of Mixed water have high salinities (>35.7) and high $\delta^2\text{H}$ values (>3 per mil), but relatively low temperatures between 16°C and 17°C . These waters are identified as cooled GABP waters and are therefore included in the GABP water mass. GABP water is hence redefined to have mid to high salinities and temperatures, and high $\delta^2\text{H}$ values.

[18] FC waters also show a range in isotopic compositions, and there appears to be two end-members: mid $\delta^{18}\text{O}$ –low $\delta^2\text{H}$ waters and low $\delta^{18}\text{O}$ –mid $\delta^2\text{H}$ waters (Figure 8).

These end-members are also spatially distinct off the shelf below the seasonal thermocline (~ 70 m). The mid $\delta^{18}\text{O}$ –low $\delta^2\text{H}$ waters occur west of 132.5°E and are identified as the FC. These off-shelf waters are adjacent to modified FC(a) shelf waters with a similar isotopic composition. The low $\delta^{18}\text{O}$ –mid $\delta^2\text{H}$ waters are present east of 132.5°E and are identified as a mixing of GABP shelf waters with off-shelf FC waters. This mixed water mass is labeled as FC + Outflow. Both FC and FC + Outflow waters are present in upwelling areas along the Eyre Peninsula. Therefore five water masses are identified in the eastern GAB based on their temperatures, salinities, nitrate contents and $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values (Table 2; Figure 9). $\delta^{18}\text{O}$ and $\delta^2\text{H}$ relationships on the shelf are predominantly defined by mixing of FC and FC(a) waters with GABP waters (Figure 10). Mixed waters on the shelf represent mixing of these end-members. In addition, increasing temperatures and salinities of the Mixed waters from east to west indicate progressive heating and evaporation of these waters on the shelf.

[19] Spatial distribution of the water masses indicates an increasing temperature and salinity gradient from east to west (Figure 11). Mixed waters are divided into water masses mixed (a) and mixed (b) to show increasing temperatures and salinities within the one water mass. At depth (Figure 11a), FC + Outflow waters are present at depth along the Eyre Peninsula. Mixed waters increase in temperature and salinity in a northwest direction along the coast. The GABP is present at the Head of the Bight and along the shelf edge to ~ 132 – 133°E , with pockets of modified FC water present in the west of the study area. At the surface (Figure 11b), Mixed waters are present over most of the shelf, with GABP waters on the mid shelf and shelf edge between 130 – 133°E . Modified FC water is also present at the surface in the west of the study area. From east to west, transects show differences in the distribution of water masses with depth (Figures 3 and 12).

4. Discussion

4.1. Shelf Circulation

[20] Hydrographic and stable isotope data outlined here support previous modeling results [Herzfeld and Tomczak, 1999; Middleton and Platov, 2003] of counterclockwise circulation within the GAB (Figure 13). There is a distinct temperature and salinity gradient from east to west across the eastern GAB, which is visible in spatial maps of the water mass distribution (Figure 11) and CTD profiles and depth transects comparing eastern, central and western areas (Figures 6 and 12). Northwesternly flowing coastal currents form one arm of the anticyclonic gyre (Figure 13). These currents are driven by westerly winds and surface Ekman transport in summer [Middleton and Cirano, 2002]. The distribution of upwelled FC + Outflow and Mixed waters reflects this northwesterly flow of water (Figure 6), as FC + Outflow is modified to Mixed waters as it flows along the coast. The returning arm of the gyre is formed from southeasterly flow of GABP water from the Head of the Bight to the shelf edge and east along the shelf break (Figure 13). This southeasterly flow has been identified from modeling and sea surface temperature satellite imagery [Herzfeld, 1997; Herzfeld and Tomczak, 1999; Middleton and Platov, 2003]. Hydrographic data herein support this southeasterly flow. At depth, there is a northwest–southeast band of GABP water

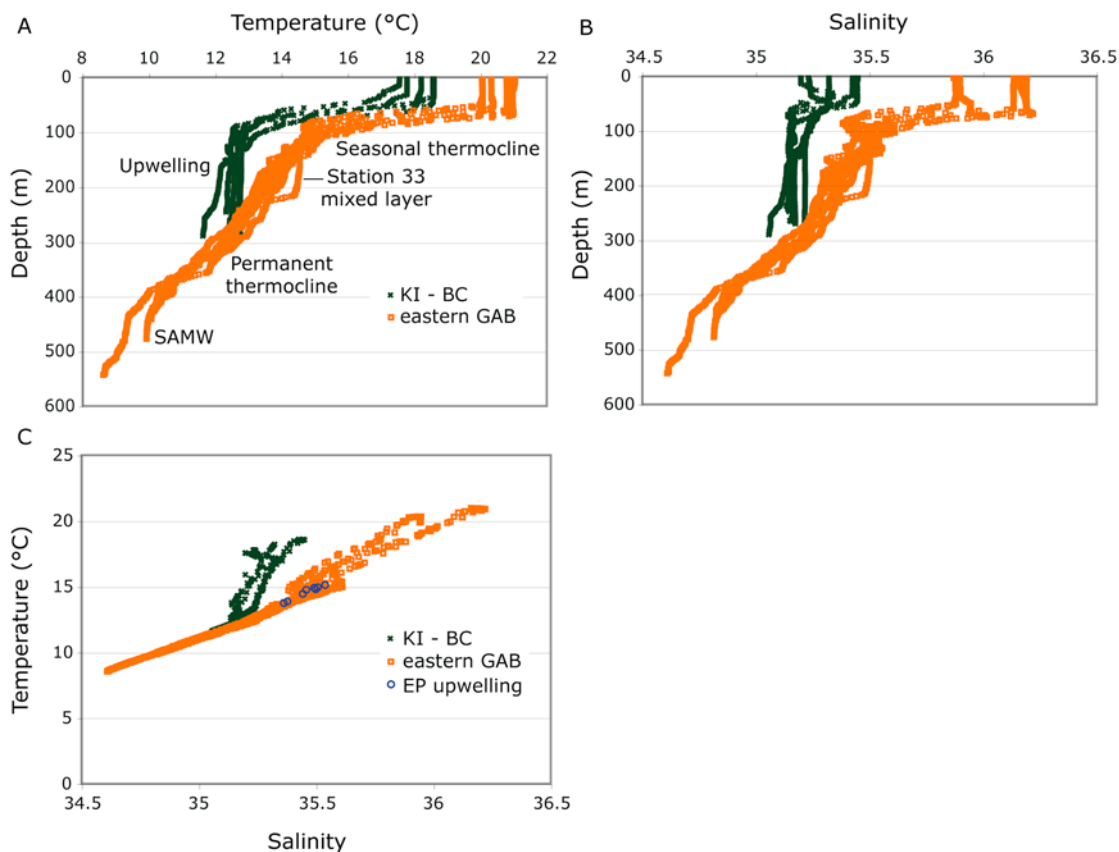


Figure 7. Off-shelf stations from Kangaroo Island and the Bonney Coast (KI-BC) and the eastern GAB (Figure 1), showing depth profiles of (a) temperature, (b) salinity, and (c) temperature versus salinity for each region. EP upwelling is upwelled waters along the Eyre Peninsula.

from the Head of the Bight to the shelf edge at $\sim 133^{\circ}\text{E}$. At the surface, Mixed water is present around the Head of the Bight, while the GABP has flowed southeastward and occupies the mid shelf and shelf edge (Figure 11).

[21] GABP water is present at the surface on the mid shelf and along the shelf edge between 130°E and 133°E . This water mass is characterized by surface temperatures above 20°C and surface salinities between 35.9 and 36.2, with all but one surface sample having salinities ≥ 36.0 . The high temperatures and salinities suggest heating and evaporation of surface waters on the shelf. The GABP is seen in satellite imagery at 134°E during March–April [Herzfeld, 1997]. The results from this study show that GABP water is more widely spread than just a distinct plume at 134°E . The highest values of $\delta^2\text{H}$ (>4 per mil) occur at the surface at stations 32, 33, 35 and 36 ($\sim 132.5^{\circ}\text{E}$), and at 50 m depth at station 44 (130.5°E) (Figure 12). No $\delta^2\text{H}$ data is available for the surface at station 44 but the CTD profile shows a well-mixed water column down to 70 m, suggesting that a similar high $\delta^2\text{H}$ value would also be present at the surface. If movement of the GABP is both southeastwards and southwards from the Head of the Bight to the shelf edge, these stations would record the greatest effect from evaporation. This increases the spatial extent of the previously defined GABP to include surface areas along the shelf edge between 130°E and 132.5°E and also suggests that there is flow southward from the Head of the Bight to the shelf edge. However, not all surface samples along this south-

ward path are GABP water; this water is mixing with modified FC water sourced from off the shelf, that has similar high temperatures and salinities but low $\delta^2\text{H}$ values.

[22] At depth, GABP water is present at the shelf edge as far east as $\sim 133^{\circ}\text{E}$, which correlates with the distinction between FC and FC + Outflow waters off the shelf. While

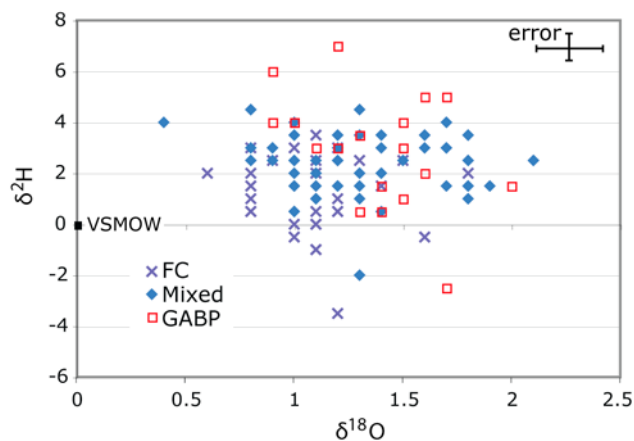


Figure 8. $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ values of eastern GAB waters, divided into distinct water masses on the basis of their temperatures and salinities. VSMOW is Vienna Standard Mean Ocean Water.

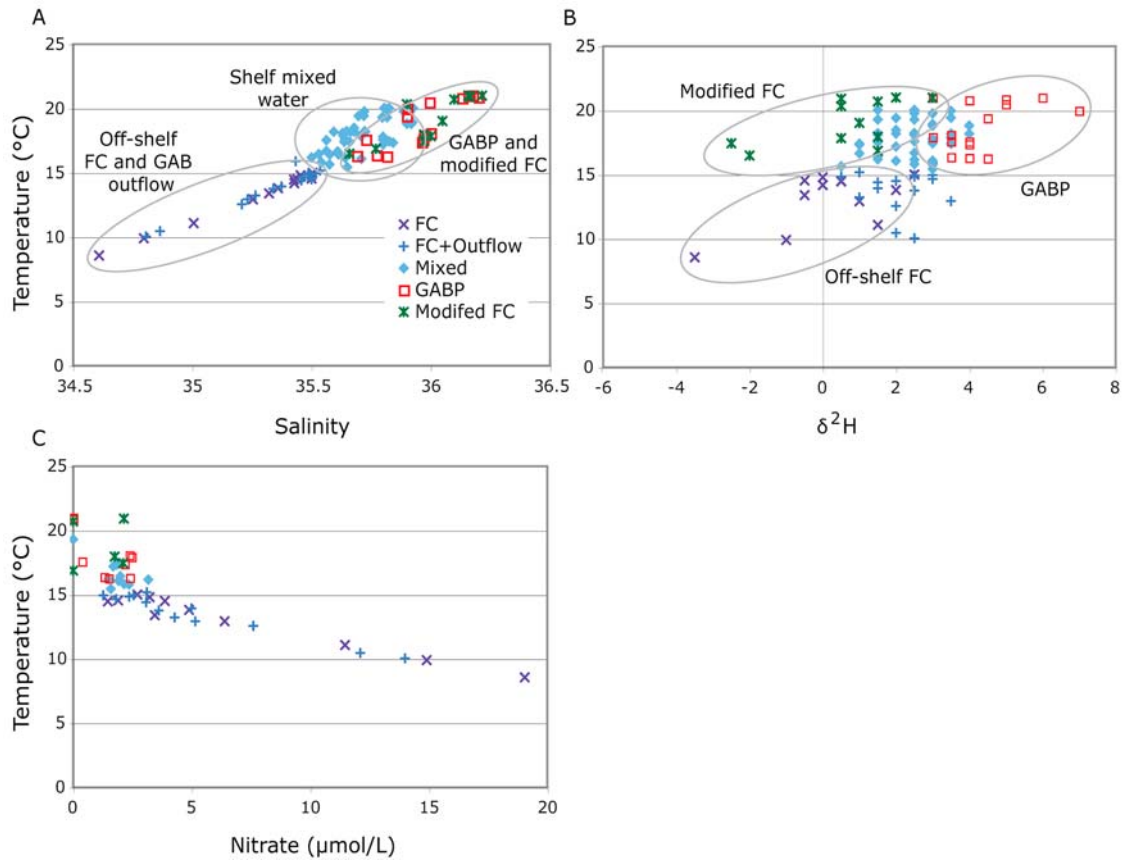


Figure 9. Relationships among (a) temperature versus salinity, (b) temperature versus $\delta^2\text{H}$, and (c) temperature versus nitrate contents of water masses in the eastern GAB, defined on the basis of their temperatures, salinities, $\delta^2\text{H}$, and $\delta^{18}\text{O}$ values: Flinders Current (FC), Flinders Current mixed with GAB outflow (FC + Outflow), Mixed waters, Great Australian Bight Plume (GABP), and modified Flinders Current.

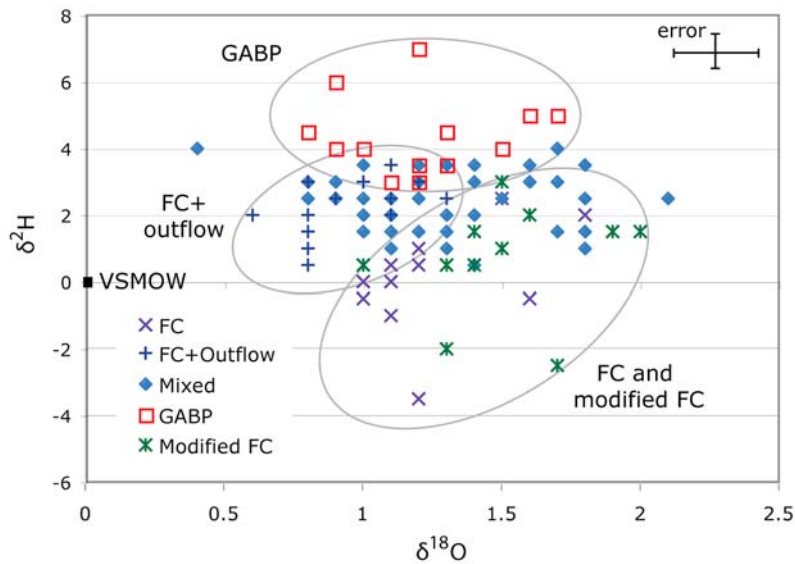


Figure 10. $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ values of eastern GAB waters, divided into distinct water masses on the basis of their temperatures, salinities, $\delta^2\text{H}$, and $\delta^{18}\text{O}$ values. VSMOW is Vienna Standard Mean Ocean Water.

Table 2. Properties of Water Masses Defined on the Basis of Temperature, Salinity, $\delta^2\text{H}$, and $\delta^{18}\text{O}$ Values: Flinders Current (FC), Flinders Current + Outflow (FC + Outflow), Mixed Waters, Modified Flinders Current (FC(a)), and Great Australian Bight Plume (GABP)

Water Mass	Temperature ($^{\circ}\text{C}$)	Salinity	$\delta^{18}\text{O}$ (per mil)	$\delta^2\text{H}$ (per mil)	Nitrate ($\mu\text{mol/L}$)
FC	<15.0	<35.5	1.0–1.8	–3.5–2.5	1.5–19.1
FC + Outflow	<15.2	<35.5	0.8–1.3	0.5–3.0	1.3–12.1
Mixed	15.4–20.0	35.5–35.9	0.4–2.1	0.5–4.0	0–3.2
FC(a)	16.5–21.0	35.7–36.2	1.0–2.0	–2.5–3.0	0–2.2
GABP	16.3–21.0	35.7–36.2	0.8–1.7	3.0–7.0	0–2.5

the temperatures and salinities of these off-shelf waters are very similar (Figure 9a), they are isotopically distinct, with FC waters having lower $\delta^2\text{H}$ and higher $\delta^{18}\text{O}$ values than the mixed FC + Outflow waters (Figure 10). The spatial boundary between the two off-shelf waters is between stations 32 and 33 at $\sim 132.5^{\circ}\text{E}$, suggesting that GABP water is flowing off the shelf in this area. The stations are very close to each other, but station 33 is closer to the shelf edge than station 32. The salinity and temperature profiles of station 33 show a higher salinity mixed layer of 14.5°C and 35.5 between 120 and ~ 210 m (Figure 7), suggesting GABP water is flowing off the shelf and mixing with FC water. To the east of station 33 this mixed layer is no longer present, likely due to mixing and equilibration of temperature and salinity. Without isotopic data to the east of the GAB and without current meter data, it is unclear which way the outflow is moving, however it influences isotopic values of waters down to 440 m. This depth is greater than expected considering that temperature and salinity appear to equilibrate quickly and therefore this water would not be overly dense. However, modeling results show mesoscale eddies within the FC along southern Australia [Arthur, 2006], which may allow for vertical mixing. The presence of these eddies may explain the influence of this outflow being observed at 440 m.

[23] The isotopic compositions of most FC + Outflow waters plot between GABP shelf waters and FC waters, supporting mixing of the two sources off the shelf (Figure 10). However, isotopic compositions of waters from station 33 show low $\delta^{18}\text{O}$ values between 0.6 and 0.8 per mil, which are lower than $\delta^{18}\text{O}$ values present in FC or GABP waters. Additions of water with low $\delta^{18}\text{O}$ values from tropical storms may provide the low $\delta^{18}\text{O}$ values observed in station 33 samples. Tropical storms can travel down the west coast of Australia and move into the GAB, and the tropical source of the rainfall would add water with low $\delta^{18}\text{O}$ values to the GAB shelf. As the shelf is poorly mixed, $\delta^{18}\text{O}$ values as low as 0.4 per mil are present on the shelf, and GABP waters adjacent to the shelf edge (surface waters at stations 33, 36 and 44), have $\delta^{18}\text{O}$ values of 0.8–0.9 per mil; therefore it is possible that the low $\delta^{18}\text{O}$ values for station 33 are sourced from shelf waters modified by precipitation.

4.2. The Flinders Current

[24] Off the shelf, waters with low $\delta^2\text{H}$ and mid $\delta^{18}\text{O}$ values represent the Flinders Current (FC). $\delta^2\text{H}$ values as low as -3.5 per mil in FC waters reflect the influence of its subantarctic or Antarctic source. The FC is sourced from Subantarctic Mode Water formed within the Subantarctic Zone, with additions from the Tasman Outflow, a remnant of the East Australian Current that sinks and flows west

around Tasmania [Cirano and Middleton, 2004]. Subantarctic Mode Water forms in various regions within the Subantarctic Zone, the largest source region being in the southeast Indian Ocean [Sallée et al., 2006], and flows east as part of the Antarctic Circumpolar Current. The FC flows from the Subantarctic Zone north and then west along the Australian continental slope as part of a major anticyclonic gyre within the South Australian Basin. There is limited isotopic data currently available to help distinguish water masses and source regions of the FC, although Meredith et al. [1999] measured $\delta^{18}\text{O}$ values of water masses within the South Atlantic. Subantarctic Surface Water in the South Atlantic, with a $\delta^{18}\text{O}$ value of 0.65 per mil, would be similar to the southeast Indian Ocean formation region of Subantarctic Mode Water, which is likely the dominant source of the FC. $\delta^{18}\text{O}$ values of ~ 1 to 1.2 per mil for the FC within the GAB region are somewhat higher than this source, however without isotopic data from the Subantarctic Zone south of Australia or the East Australian Current, it is not possible to further explain the observed values. It is also not understood why the FC has a high $\delta^{18}\text{O}$ but low $\delta^2\text{H}$ value. Major sea ice formation can increase the $\delta^{18}\text{O}$ value of seawater at a greater rate than the $\delta^2\text{H}$ value, however fractionation factors between ice and water are of similar magnitude to fractionation factors between water and vapor during evaporation [Friedman and O'Neil, 1977], and should not result in such high $\delta^{18}\text{O}$ but low $\delta^2\text{H}$ values. It is possible that there is some unknown meteoric input into the region such as groundwater or sediment pore waters that may change isotopic ratios, however it is assumed that the influence of such waters would be localized rather than so widespread.

[25] The FC has not been defined hydrographically; instead it is classed as westward flow along the continental slope [Middleton and Cirano, 2002; Middleton and Platov, 2003]. The core of westward flow and hence the FC is within the permanent thermocline [Middleton and Platov, 2003], which was between ~ 270 and 400 m during March 1998 (Figure 7). However, most current meter and modeling studies of the FC focus on intermediate depths and very little is known about the presence of the FC within the top 300 m. It is well known that during winter, a strong eastward flowing LC is present within the top 250 m along the GAB shelf break, so that the FC would be present below this depth. However, during summer when the LC is absent, it is unclear what surface currents are present and in what direction they are flowing. While there is no current meter data for March 1998, salinity and temperature profiles do not suggest changing flow direction between the seasonal thermocline (~ 70 m) and the permanent thermocline (~ 270 m) in the eastern GAB (Figure 7). Salinity and temperature values appear to decrease gradually and there are no well-defined or spatially

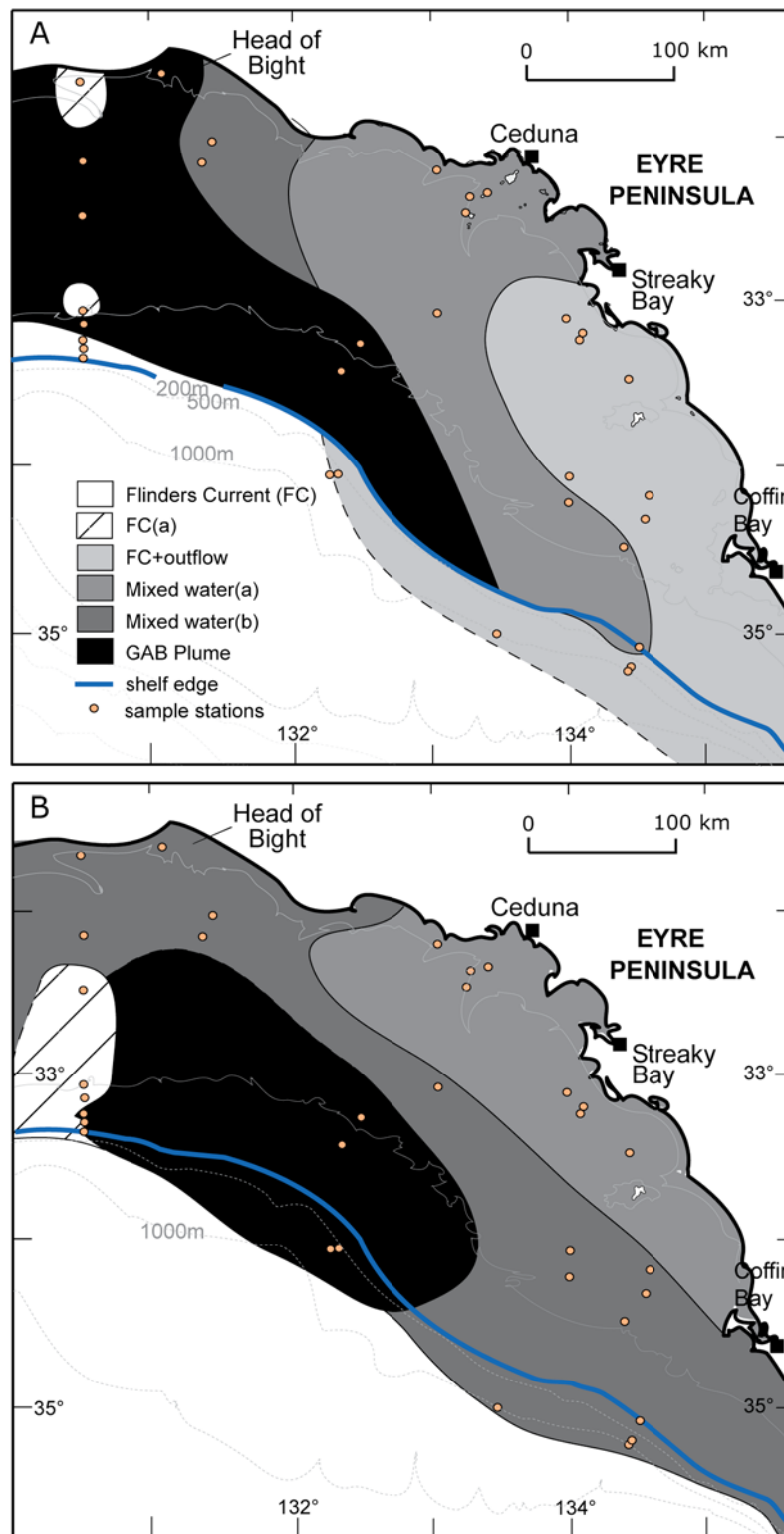


Figure 11. Charts showing the spatial distribution of water masses defined on the basis of their temperatures, salinities, $\delta^2\text{H}$, and $\delta^{18}\text{O}$ values at (a) bottom depths and (b) at the surface. The dashed line represents the estimated extent of FC + Outflow waters. Station locations are also shown.

consistent mixed layers present. In addition, high dissolved oxygen values of $>240 \mu\text{mol/L}$ are present as shallow as 120 m depth, which match values of Subantarctic Mode Water [McCartney, 1977], a water mass that flows west as

part of the FC [McCartney and Donohue, 2007]. Current meter data and additional isotopic data of the FC and its source regions are needed to confirm flow direction and the presence of the FC above the permanent thermocline.

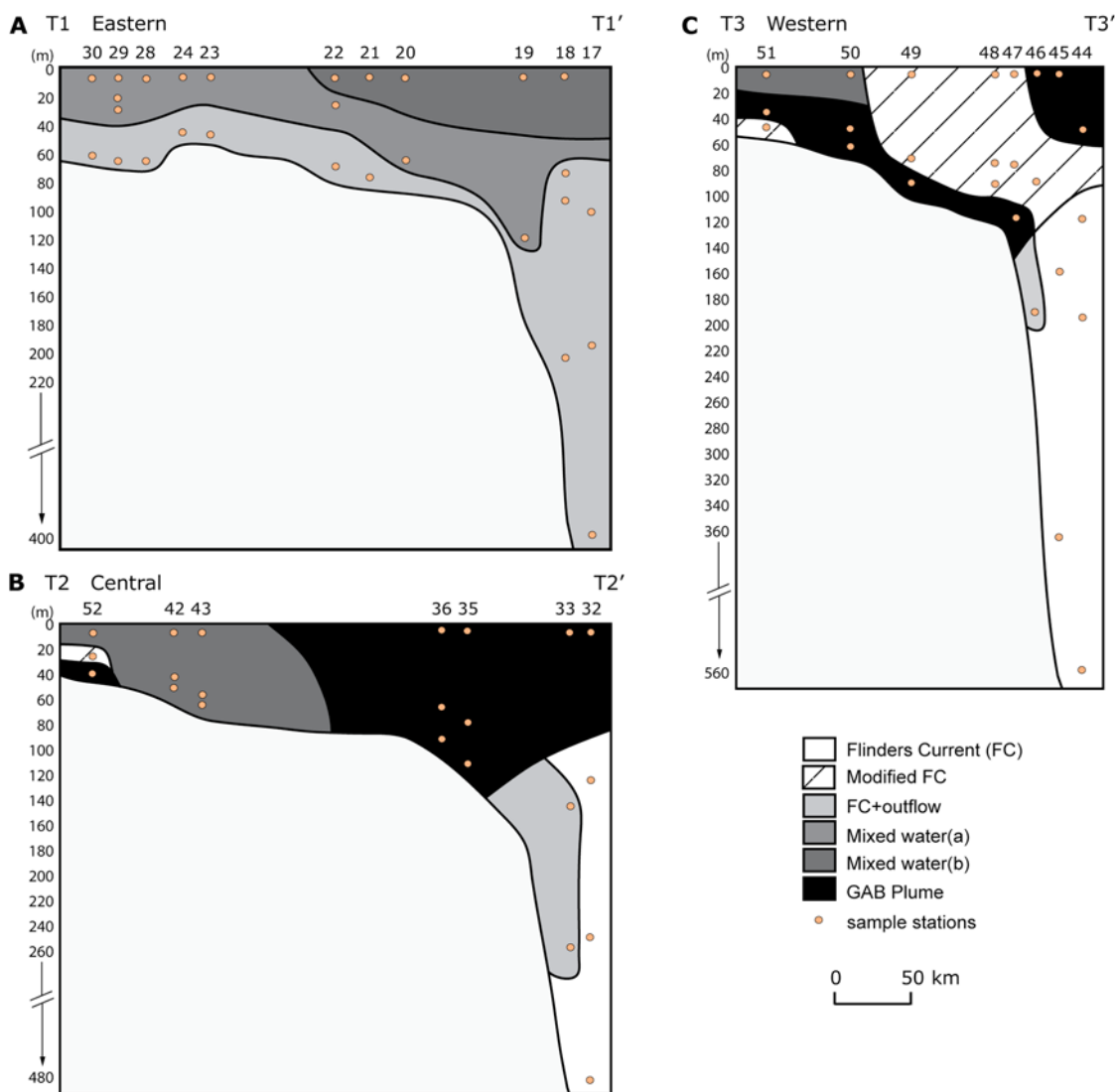


Figure 12. Transects of the (a) eastern, (b) central, and (c) western parts of the study area (Figure 3), showing water masses defined on the basis of their temperatures, salinities, $\delta^2\text{H}$, and $\delta^{18}\text{O}$ values. Sample locations are also shown.

4.3. Eyre Peninsula Upwelling

[26] Bottom waters along the Eyre Peninsula match FC + Outflow waters present off the shelf, with temperatures and salinities of $<15.2^\circ\text{C}$ and <35.5 (Figure 9a). Temperature and salinity properties match FC + Outflow waters and do not match upwelled water from Kangaroo Island and the Bonney Coast (KI-BC; Figure 7c). Bottom waters along the Eyre Peninsula match water properties present at ~ 150 m in stations 17 and 18, suggesting that this upwelled water is being sourced directly from the shelf break around stations 17 and 18 (134.5°E). Temperature and salinity depth profiles of FC water (Figures 5a and 5b) also support upwelling from ~ 150 m, as temperatures and salinities of samples show little variation between this depth and the surface. Nitrate contents of bottom waters at stations 21 and 22 on the shelf, however, match nitrate contents observed in waters around 250 m off the shelf (Figure 5c). Waters from 200 m at station 17 off the shelf have lower nitrate values than bottom waters from

stations 21 and 22, suggesting that off-shelf water at 150 m may not be the only source of upwelled water on the shelf, as nutrient contents are too low.

[27] Previous research on upwelling events in the eastern GAB suggest that water is sourced from shelf-break upwelling off Kangaroo Island (KI), where it is then advected toward the western Eyre Peninsula by the westerly coastal currents [Kämpf *et al.*, 2004; McClatchie *et al.*, 2006; Middleton and Bye, 2007]. McClatchie *et al.* [2006] presented temperature data to show the KI “pool” with water $<14^\circ\text{C}$, being advected along the coast toward the eastern GAB between the 100 and 200 m isobaths. Temperatures of bottom waters at stations 21 and 22 match those of the KI “pool”, and the higher nitrate contents at these stations may be explained by advection of this deep upwelled water into the eastern GAB. Apart from these two stations, however, the temperature, salinity and nutrient characteristics of the remaining upwelled waters are consistent with

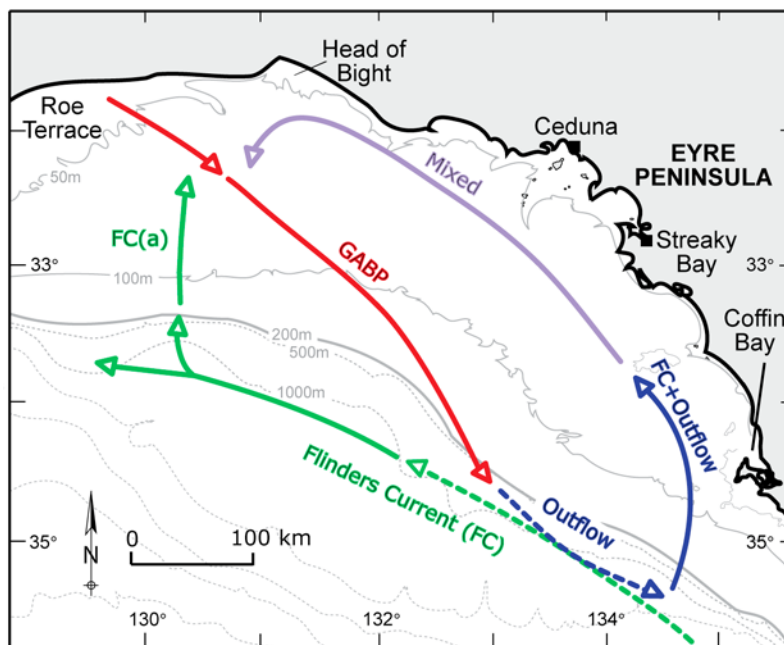


Figure 13. Schematic diagram of currents in the eastern GAB shelf. The five water masses, Flinders Current, modified Flinders Current (FC(a)), Flinders Current mixed with GAB Outflow (FC + Outflow), Mixed waters, and Great Australian Bight Plume (GABP), display anticyclonic circulation on the shelf. Dashed lines of Flinders Current and Outflow represent the estimated mixing of these two currents to form the FC + Outflow water mass.

water being sourced directly from the shelf break. As coastal currents flow west between KI and the GAB, it is conceivable that some upwelled water from KI flows along the shelf and into the eastern GAB. Therefore the cool, fresh water residing at depth along the Eyre Peninsula may be a combination of off-shelf water and upwelled water from off KI, and this KI upwelling signature is displayed most prominently in nitrate contents of waters from stations 21 and 22, the closest eastern GAB shelf stations to KI. Stable isotopic compositions of upwelled waters show a mix of both FC and FC + Outflow signatures. As the cool, fresh upwelling water along KI and the Bonney Coast is the FC [Lewis, 1981; McLeay *et al.*, 2003; Ward *et al.*, 2006; Middleton and Bye, 2007], $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of Eyre Peninsula upwelled waters suggest a combination of eastern GAB shelf-break and KI sources. Therefore hydrographic data in conjunction with stable isotope data support the theory that Eyre Peninsula upwelled waters are predominantly sourced from off-shelf water around stations 17 and 18, with addition of water from upwelling around KI. As off-shelf water around stations 17 and 18 is mixed FC + Outflow waters, it appears that GABP waters flow off the shelf, mix with FC waters and are upwelled back onto the shelf along the Eyre Peninsula (Figure 13).

[28] Nitrate contents of upwelled waters are not remarkably high. Stations 21 and 22 display nitrate contents close to $5 \mu\text{mol/L}$, but the remaining samples are between 1.3 and $3.9 \mu\text{mol/L}$, which match with nitrate contents above 200 m in stations 17 and 18 (Figure 5c). Modeling by Baird [2003, cited from McClatchie *et al.*, 2006] predicted that on the broad, shallow shelf of the eastern GAB, upwelling would occur at the shelf break rather than inshore, and nutrients would be quickly utilized by phytoplankton before reaching

the surface. This could explain values as low as $1.3 \mu\text{mol/L}$ in waters sourced from $\sim 150 \text{ m}$ depth. Dissolved oxygen values in waters from both eastern (Figure 5d) and off-shelf stations show a distinct oxygen peak at the bottom of the seasonal thermocline. These values reach $\sim 290 \mu\text{mol/L}$ at 100 m off the shelf and $\sim 315 \mu\text{mol/L}$ at 40 m on the shelf. Both above and below these depths dissolved oxygen contents are lower. Dissolved oxygen contents of waters are $\sim 240\text{--}250 \mu\text{mol/L}$ at $\sim 150 \text{ m}$ off the shelf, and these values remain constant down to the deepest sample at 540 m depth. Therefore upwelling of water from $\sim 150 \text{ m}$ cannot explain such high oxygen values of $\sim 315 \mu\text{mol/L}$ at 40 m on the shelf, so oxygen must be sourced by another mechanism.

[29] It is possible that primary productivity is increasing the dissolved oxygen content of the water, as suggested by Riser and Johnson [2008] in the oligotrophic Pacific subtropical gyres. They found maximum net community production and dissolved oxygen contents at the bottom of the pycnocline, which correlates with observations of a dissolved oxygen peak at the bottom of the seasonal thermocline and pycnocline in the eastern GAB. Analysis of a major upwelling event from 3 to 10 March 1998 in the eastern GAB by Kämpf *et al.* [2004] showed that a week after the upwelling event, a distinct subsurface chlorophyll *a* maximum with values 10x that of the ambient water developed at a depth of 50 m . This depth matches the bottom of the seasonal thermocline and the dissolved oxygen peak seen in station 21 (Figure 6c), though it is deeper than other upwelling stations along the coast (22, 23 and 24), which have oxygen peaks between 20 and 40 m . Kämpf *et al.* [2004], however, only published chlorophyll *a* results from the surface and from 50 m depth; therefore the depth of the

chlorophyll *a* maximum may vary across the upwelling stations and match the depth of the seasonal thermocline.

4.4. Central GAB Upwelling

[30] Modified FC water (FC(a)) is present in the western part of the study area along the north–south sampling transect at 130.5°E (Figures 11 and 12). This water has similar $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values as off-shelf FC water but has similar temperatures and salinities as GABP waters. Its spatial occurrence on the shelf matches the occurrence of FC water off the shelf, suggesting there is intrusion of FC water onto the shelf in this area, which is then modified by mixing with GABP water. Some mechanism is needed to bring this water onto the shelf. There is no mention of such a mechanism in the literature; rather the area has been defined as a region of downwelling [James *et al.*, 2001; Middleton and Bye, 2007]. Most modeling studies, however, focus on the southeasterly movement and downwelling of the GABP off the shelf $\sim 135^\circ\text{E}$ and very little is known about downwelling $\sim 130^\circ\text{E}$. No downwelling is observed in this area in March 1998, where FC water is adjacent to modified FC(a) water (Figure 12c). Middleton and Platov [2003] mention an onshore component of the FC while modeling summer circulation in the GAB region. In the western half of the bight, a ridging in sea level is formed from the convergence of the onshore FC with offshore topographic Sverdrup transport. This onshore component of the FC may be what is observed in the central bight during March–April 1998.

[31] There is no enrichment of nitrate in this region of upwelling (Figure 9c). Nitrate is depth dependent in off-shelf stations, and no distinction is made between FC and FC + Outflow waters. Below 200 m, nitrate is $>3 \mu\text{mol/L}$; between 120 and 140 m, nitrate is between 1 and 2 $\mu\text{mol/L}$, and above this nitrate is negligible, suggesting that any available nutrients are being used up quickly within the photic zone. Nitrate contents of modified FC(a) waters show a range of 0 to 2.1 $\mu\text{mol/L}$, similar to values in Mixed and GABP waters. This suggests that FC waters may be flooding onto the shelf from depths less than 140 m rather than from depths where higher nutrient contents prevail. Dissolved oxygen is generally low; while there is some increase in oxygen below the seasonal thermocline, it is not very significant, especially compared to the increase observed in eastern stations (Figure 6c). This suggests that there is no significant primary productivity adding dissolved oxygen to the water, or that secondary producers are quickly using up any dissolved oxygen created. Also, mixing with nutrient-depleted GABP waters would result in low nutrient contents of waters in this area.

5. Conclusions

[32] Five water masses are identified on the eastern GAB shelf using hydrographic and stable isotope data on waters sampled during March–April 1998. Two of these are end-member water masses, the FC and the GABP, and the remaining three result from mixing, heating and evaporation of these two end-members on the shelf. $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of FC waters are generally -1.0 to $+1.0$ per mil and $+1.0$ to $+1.2$ per mil, respectively, whereas $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of GABP waters range from $+3.0$ to $+7.0$ per

mil and 0.8 to 1.7 per mil, respectively. $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values of waters discriminate mixed water masses that are indistinct from the FC and GABP on the basis of their temperatures and salinities: (1) a high temperature and salinity, low $\delta^2\text{H}$ water mass that occurs spatially with and has similar temperatures and salinities as the GABP, but has a similar isotopic signature to the FC, and (2) isotopically distinct off-shelf waters east of $\sim 132^\circ\text{E}$ that suggest GABP waters are flowing off the shelf and mixing with FC waters in this area. These water masses are identified as modified FC and FC mixed with outflow waters, respectively. The final water mass occurs across the shelf and is a mixture of these four water masses.

[33] The distribution of these water masses reflects an anticyclonic gyre within the eastern GAB, showing progressive mixing, heating and evaporation as water flows in a northwesterly direction along the coast to the Head of the Bight and then in a southeasterly direction toward the shelf edge (Figure 13). Cool and fresh upwelled FC waters present along the Eyre Peninsula mix with shelf waters and are heated and evaporated as they flow around the gyre. These waters mix with GABP waters around the Head of the Bight, which then flow southeastwards to the shelf edge. The occurrence of GABP waters along the shelf edge between 130° and 133°E suggests that flow of water is also southwards from the Head of the Bight to the shelf edge.

[34] Temperature and salinity properties of cool and fresh water present at depth along the Eyre Peninsula in the east of the study area match properties from stations at the shelf break, suggesting that water is flooding onto the shelf directly from the eastern GAB rather than being advected from Kangaroo Island east of the study area. This upwelled water is a combination of FC and GAB outflow water, therefore GABP water flows off the shelf, mixes with the FC and is incorporated into upwelling along the Eyre Peninsula. This upwelled water matches temperatures and salinities occurring at ~ 150 m at the shelf break, implying upwelling from this depth. Nitrate contents in some upwelled waters are higher than those at the shelf break at ~ 150 m depth, suggesting some addition of nutrient-rich, deep upwelled water from Kangaroo Island, which is advected along the shelf and into the eastern GAB. The presence of modified FC water in the west of the study area indicates upwelling of FC water onto the shelf around 130°E , however this water does not appear to supply nutrients onto the shelf.

[35] The complex relationships observed among isotopic compositions, salinity and temperature in the eastern GAB are attributed to a combination of mixing and evaporative processes occurring on the shelf. Waters from two isotopically and hydrographically distinct water masses mix both on and off the shelf, and GAB outflow waters that have mixed with the FC are incorporated into upwelling along the Eyre Peninsula to recirculate around the gyre. Further hydrographic and isotopic information of the regional FC and the Leeuwin Current, which is dominant on the shelf in winter and would likely be the source of remnant shelf waters during summer, would allow for greater understanding of mixing processes occurring on the shelf. Isotopic information of off-shelf water to the east of the GAB would help clarify the role of deep upwelling off Kangaroo Island along the Eyre Peninsula, and the interactions between and eastward extent of the FC and GAB outflow waters.

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