RESEARCH REPORT SERIES

Theme 1: Physical Oceanography of the Great Australian Bight

THEME REPORT

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GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

The Great Australian Bight Research Program is a collaboration between BP, CSIRO, the South Australian Research and Development Institute (SARDI, the University of Adelaide, and Flinders University. The Program aims to provide a whole-of-system understanding of the environmental, economic and social values of the region; providing an information source for all to use.

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ACKNOWLEDGEMENTS

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1. EXECUTIVE SUMMARY

To understand the circulation within the Great Australian Bight (GAB), three distinct hydrodynamic models were used; two shelf-focused models (ROMS and SHOC) for the four year period 2011 to 2014 and one deep-sea focused model (BRAN) for the 23-year period 1994-2016. Good to very good agreement between shelf model hind-casts and data were found for the shelves and at depths less than 200-300 m. Further offshore, the shelf models were unable to replicate aspects of the important observed features of the meso-scale eddy fields. The implication of this is that the regional model results are only reliable inshore of the 300 m isobath.

During both winter and summer, the model results were as expected from previous studies summarised by Middleton and Bye (2007). However, the results here were obtained at higher resolution and with more realistic forcing and initial fields of stratification. The winter mean circulation was found to be to the east and characterised by (i) the shelf edge Leeuwin Current (LC) in the west to central GAB, (ii) the shelf edge South Australian Current (SAC) in the east (both ~ 20 cm/s) and (iii) a nearshore eastward Coastal Current (CC) (~ 10 cm/s). Strong evidence was also found for a deep (500 m) westward Flinders Current (FC).

Atmospheric cooling and evaporation also enhance the bottom boundary layer downwelling and outflow that extends across the GAB. During summer, the mean winds reverse to circulate in an anti-clockwise manner within the GAB. The mean CC reverses in the eastern GAB leading to upwelling. An anti-clockwise gyre is found in the central GAB driven by (i) the westward CC, (ii) southward topographic Sverdrup transport, and (iii) an eastward SAC at the shelf edge. The southward Sverdrup transport leads to downwelling at the shelf edge and raises sea level, that in part seems likely to drive the summertime SAC. This, and the role of density gradients in driving the SAC, remain an important area for future investigation.

The winter and summer circulation is punctuated by the passage of low and high pressure systems that lead to wind-band variability (3 -30 days) of up to 1 m/s in the eastern GAB. The two shelf models provided good to very good hind-casts of much of the observed variability in shelf ocean currents using data obtained from 6 moorings over the 2011-2014 period. The shelf tidal signals were also well reproduced by the shelf models along with the seasonal variability in monthly averages of shelf currents.

The above studies were complemented by an analysis of 23 years of the BRAN global model output to show that while the LC has a strong seasonal cycle (up to 5.5 Sv), the inter-annual variation can exceed the seasonal variation and be up to 8 Sv in some years and zero in others. The existence of a deep westward FC is supported by the BRAN model and other results. The results and additional focused studies were conducted to assist other themes in the Great Australian Bight Research Program (GABRP), notably for nutrient paths of connectivity and origins of hydrocarbon seeps such as tarballs.

A project of the Oceanography Theme was to investigate the possibility that the large waves of the GAB should be taken explicitly into account when modelling the circulation. To this end, we performed numerical experiments in which many of the coupling terms between the winds, waves and circulation were explicitly represented, rather than merely parameterised. Two independent modelling systems were used (ROMS and SHOC). The results were inconclusive – partly because the two models gave different results and the potential improvements of model accuracy could not be verified by the limited amount of available field measurements of critical quantities. We therefore concluded that the traditional approach to modelling the circulation (by ignoring the coupling

between waves and the circulation) was an adequate approach to modelling the circulation (especially the subsurface circulation) of the GAB.

2. INTRODUCTION

2.1 Overview

The broad-scale features of the physical oceanography of the Great Australian Bight (GAB) are thought to be well-known and are summarised in the review paper of Middleton and Bye (2007). However, gaps in our knowledge exist due to the relative paucity of *in-situ* ocean data for the region and lack of realistic modelling of the region. Previous studies were conducted over 15 to 20 years ago (notably Middleton and Platov, 2003) and confirmation of those results was an implicit goal of the Oceanography Theme of the Great Australian Bight Research Program (GABRP). In this research theme, we developed two high resolution hydrodynamic models (ROMS and SHOC) and where possible validated them against moorings and other *in-situ* data.

High current speeds (>1 m/s) are known to occur near the sea surface as a result of local wind forcing although the predictive skill by models remains to be determined. The cross-shelf exchange of nutrients driven by wind-forcing appears to be important in determining the shelf distributions of neritic sediments which characterise the benthos of the GAB (Middleton et al., 2014); these carbonate sediments make the southern shelves the largest temperate carbonate factory in the world. However, these inferences regarding the benthos were made using an idealised model of the mean summer circulation of the GAB (Middleton and Platov, 2003) in which the stratification was poorly determined. In addition, the GAB is subject to inflows over the shelf of the warm Leeuwin Current (LC) (Cresswell and Griffin, 2004), as well as a hypothesised shelf-slope Flinders Current (FC); the latter is thought to flow from east to west and provide a deep (400-700 m) conveyor belt for nutrients along the shelf edge (see Middleton and Cirano, 2002; Middleton and Bye, 2007). However, evidence for this current is largely indirect and has been inferred from water mass analyses (Richardson, 2015). There is a need to obtain observational evidence to confirm or refute the existence of the FC. A major influence on the circulation of the GAB is the LC, which enters the GAB as a flow along the upper slope and outer shelf, especially during the winter months. The strength of the LC is known to depend on the El Nino / La Nina cycle which has a multi-year timescale, so studies of its variability preclude the use of the ROMS and SHOC models developed for studies of the 2011 to 2014 period. Instead we examined decadal variability using the Bluelink 23-year global ocean reanalysis (BRAN2016).

It is well known that oceanic currents, sea water temperature and nutrient concentrations can have a direct impact on both benthic and pelagic ecosystems. In the latter case, the summer upwelling of nutrients off Kangaroo Island and in the eastern GAB has been shown to be important to the growth of phytoplankton, zooplankton and pelagic fish communities (Ward et al., 2006; Van Ruth et al., 2010 a, b).

Fronts and eddies are known to support pelagic communities of Southern Bluefin Tuna (Hobday et al., 2011), as well as prey (e.g. sardines) that feed upon phytoplankton that in turn, can arise from localised upwelling. The depths from which water can be upwelled are unclear, although Kaempf et al. (2004) and Richardson (2015) suggested, from water mass analysis, that these are greater than 350 m. Recent analyses of data (Petroleum Geology and Geochemistry Theme of the GABRP suggest that the asphaltite and hydrocarbon tarballs found along the southern coast may arise from the deep slope of the GAB. This result outlines the need for particle tracking studies of connectivity of

the region. The onshore Stokes drift associated with surface waves and swell may also be important to asphaltite and tarball movement and the coastal settlement of fish larvae spawned offshore.

The Oceanography Theme of the GABRP was designed to provide the physical oceanographic information that is needed to detail and verify the shelf circulation and also to underpin analyses and science that arises in several of the other research themes, notably the Pelagic Ecosystem and Environmental Drivers and the Petroleum Geology and Geochemistry Themes. In each of these themes, there is a need to understand the ecosystems and/or physical environment and the nature and dependency on the ocean physics.

A common need of several of the GABRP themes is for easily accessible (and improved) ocean colour products including chlorophyll-*a* and dissolved organic matter. The improvement of and confidence in these products has been the goal of the Australian Integrated Marine Observing System (IMOS) Bio-Optical Working Group for several years. We have worked with this group and others to provide the basic products to the Themes, and where possible, improvements (or limitations) made using *in situ* data.

3. PROJECTS

3.1 Project (1.1): Physical Oceanography of the Great Australian Bight: the science that underpins.

3.1.1 Objectives

1) To develop high resolution hydrodynamic models of the GAB that will be compared and calibrated with available data.
2) To analyse these models and data to produce the best representation and understanding of the circulation of the GAB.
3) Through particle tracking, determine the ocean flows and pathways that connect the deep, slope regions of oil and gas exploration, to the shelf and coast.
4) Provide the Benthic Biodiversity Theme with maps of bottom currents and stress to qualitatively evaluate ocean current influence on the distribution of benthic sediments.
5) Provide particle tracking information to the Petroleum Geology and Geochemistry Theme, to determine the likely origins of tar balls along the coast of the GAB and southern shelves.
6) In collaboration with the other themes, determine the likely hot-spots of ecosystem activity and physical drivers (e.g. upwelling, downwelling, mixed-layer thickness, temperature and fronts) that may be important to the dynamics of various trophic levels (from pelagic prey species to top-level predators).
7) Where possible improve the ocean colour data and provide easier acquisition as a product deliverable to other Themes.
8) To estimate the heat and volume transport of the Leeuwin Current at the Head of the Bight over a 25-year period.

The models adopted include the ROMS model (myroms.org.au), SHOC (http://www.emg.cmar.csiro.au/www/en/emg/software/EMS/hydrodynamics.html) and the global BRAN2016 model (Oke et al., 2013a, b).

3.1.2 Key results and discussion: mean summer circulation

Large scale current structures:

In summary, the summer average ROMS and SHOC model shelf circulation (Fig 3.1.1) were similar to that expected and consists of several current features that influence and are influenced by the thermohaline fields and downwelling. In particular, the ROMS and SHOC results indicate the expected anti-cyclonic circulation in the central GAB, with a westward upwelling favourable Coastal Current (CC) and southward (topographic Sverdrup) transport over the shelf and eastward South Australian Current (SAC).

For both models, the SAC was also found in the eastern GAB. Inshore of the SAC (and over the shelf), both models and data exhibited both very weak westward and eastward flows that are respectively consistent with an upwelling and downwelling favourable circulation. The lack of consistency arises from the fact that neither (weak) flow dominates near the coast during summer, and upwelling in the eastern GAB occurs as several events. Farther to the west and in the central GAB, a westward coastal current (CC) was found (Figure 3.1.1) (associated with upwelling) using ROMS and SHOC.

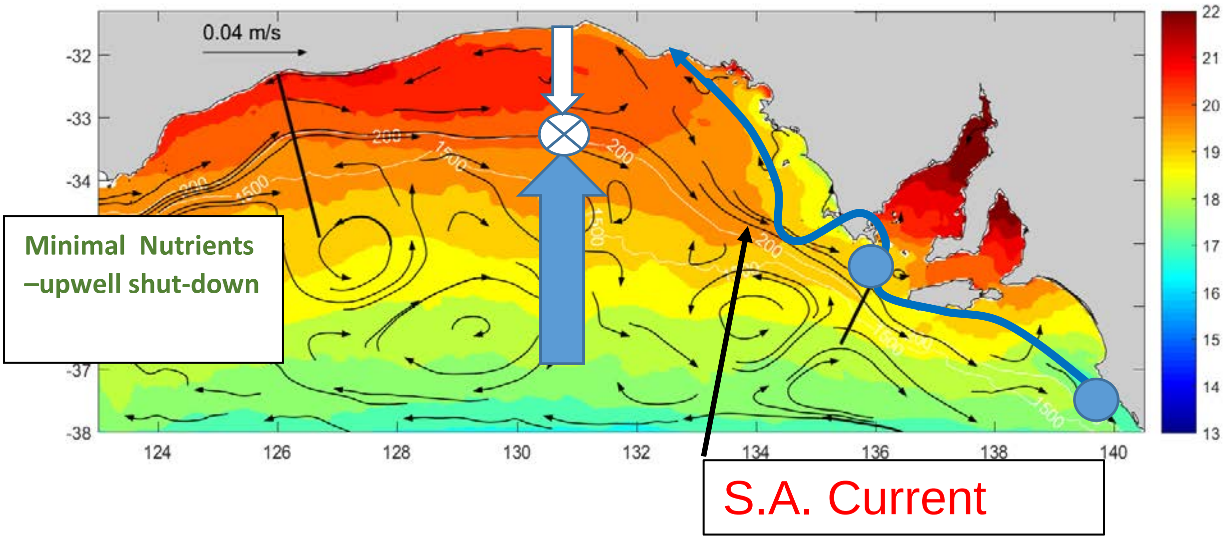

Figure 3.1.1 Plan-view of the ROMS mean summer circulation and SST. A legend vector of 0.04 m/s is shown and the colour bar at the right, Units ^{o}C). The 200 and 1500 m isobaths are shown in white. The grey and white arrows indicate the deep ocean and topographic Sverdrup transports respectively that result in downwelling ⊗. The nutrient paths are indicated by the blue arrows near the coast and source locations by the blue icons .

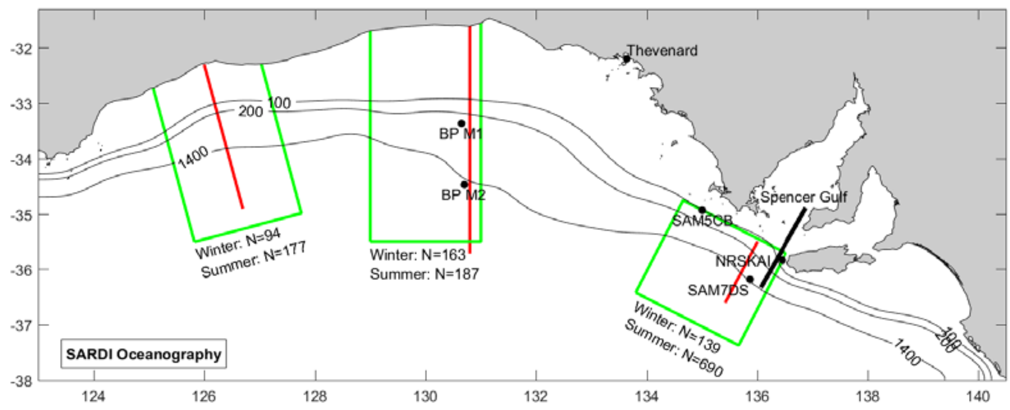

Figure 3.1.2 The ROMS model domain used in this study. The 100 m, 200 m and 1400 m isobaths are shown. The mooring locations of SAM5CB (Coffin Bay), NRSKAI (Kangaroo island), SAM7DS (deep 600 m mooring) and the BP moorings BPM1 (shelf edge) and BPM2 (shelf slope) are shown. The thick straight black line indicates the repeat SAIMOS CTD line. The red lines denote the location of cross-sectional (seasonal averaged) model results that are presented below. The green boxes denote the domains for which all available temperature data is obtained so as to compare with the (red line) cross section model results. The number (N) of temperature data casts for each green box is indicated for summer and winter.

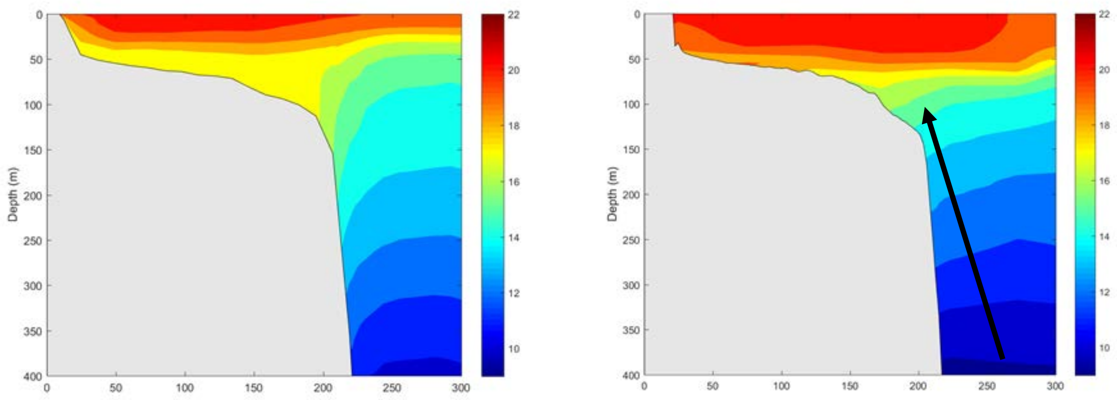

Figure 3.1.3 The ROMS (left panel) and observations (right panel) of the summer averaged temperature for the central GAB section at 130.8 ° E. The colour bar is on the right; Units ° C). A possible nutrient path to the shelf is indicated black arrow from the deep NO_2 reservoir located at depths of 300 -400 m; this might be driven by double diffusion, mechanical turbulence or convective overturning.

Downwelling:

Both models and data (Figure 3.1.2 and 3.1.3) indicated downwelling has occurred in the top 400 m. Such downwelling in the east is likely a residual from the previous winter. However, in the west to central GAB, the downwelling is also likely driven by the convergence of Sverdrup transports as described by Middleton and Platov (2003). These authors also outline how this convergence can act to enhance the strength of the SAC. These results and those for winter, strongly suggest that

downwelling is found all year round in the central GAB as also indicated by an analysis of neritic carbonate benthic sediments (Middleton et al., 2014). Active summertime shelf edge downwelling was also found in idealised numerical experiments assuming an (initially flat) distribution of nitrates.

Coastal upwelling:

Surface upwelling is not found in the far western GAB even though the mean summer winds are approximately directed in the alongshore direction and upwelling favourable. This observation is consistent with the analysis of Middleton and de' Oliveira (2017) who have shown that upwelling in the west is likely shut-down by coastal trapped wave propagation from Cape Leeuwin. Upwelling is indicated by the sea surface temperature (SST) data along the Bonney Coast (BC) and off the Eyre Peninsula, but less so in the models. The lack of consistency may be due to the relatively weak upwelling currents for the eastern GAB. Both ROMS and to a larger extent SHOC exhibit SST patterns that are consistent with the data and upwelling between the BC and Eyre Peninsula.

Nutrient paths:

The possible nutrient paths during summer, based upon the above, are as follows. Classical Ekman and topographic induced (submarine valleys and canyons) circulation can drive nutrient upwelling from the BC in the east to the Eyre Peninsula and Ceduna as indicated by the grey curves and icons in Figure 3.1.1 The upwelling in the west appears reduced and nutrient input minimal. In the central GAB, downwelling occurs all year round but processes not included or well modelled might raise nitrates from depths of 300 m to the shelf proper (80 m) as indicated in Figure 3.1.3; these include mechanical mixing, double diffusion and convective (non-hydrostatic) overturning.

Deep thermal structure and FC:

Between depths of 400 to 1500 m, the cross-sections of observed temperature at the western GAB cross-section (126 ^{o}E) and shown in Figure 3.1.4 indicate deep upwelling (isotherms raised by 100 m) for both the summer (left panel) and winter (right panel) seasonal averages. This is in contrast to the downwelling found in the top 400 m during both summer and winter (Figure 3.1.3). Middleton and Platov (2003) suggested that this deep dense upwelled water would sit lower in the water column leading to a sea level field that would enhance the SAC. Farther to the east, the deep upwelling is less pronounced or absent but the SAC still quite strong: a second explanation may involve the cross shelf density gradients that see warmer lighter water over the shelf compared to that of the deep ocean. This remains a gap in our understanding of the causes of the SAC.

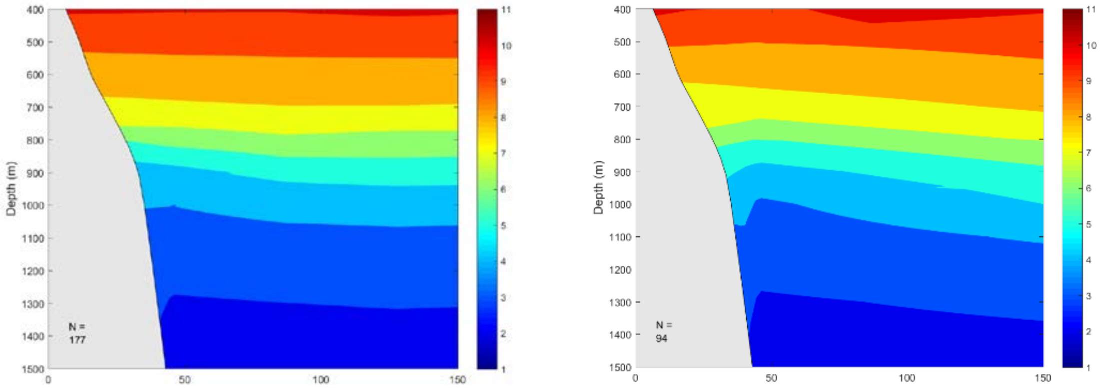

Figure 3.1.4 The cross-section at 126 ^{o} E for the summer average (left panel) and winter average (right panel) observed temperature at depths of 400 to 1500 m. Temperatures are indicated by the colour bars on the right (Units, ^{o}C).

Middleton and Cirano (2002) and Middleton and Bye (2007) argue that such upwelling is associated with the deep westward FC which is strongest in the west. Further evidence for this is given by the global BRAN2015 model currents shown in Figure 3.1.5. The currents represent 5 year averages (2001-2015) and are shown for a depth of 550 m. As is evident, the FC according to Figure 3.1.5 extends across the entire GAB, but is largest in the west (~ 10 cm/s). It is quite weak at the site of the BP shelf slope mooring in 1400 m of water where the mean value is 1 cm/s to the west. This description of the FC is consistent with water mass analyses made by Richardson (2015) who inferred its existence by the presence of deep water masses that are formed off the west coast of Tasmania but found in the far west at Albany and Cape Leeuwin.

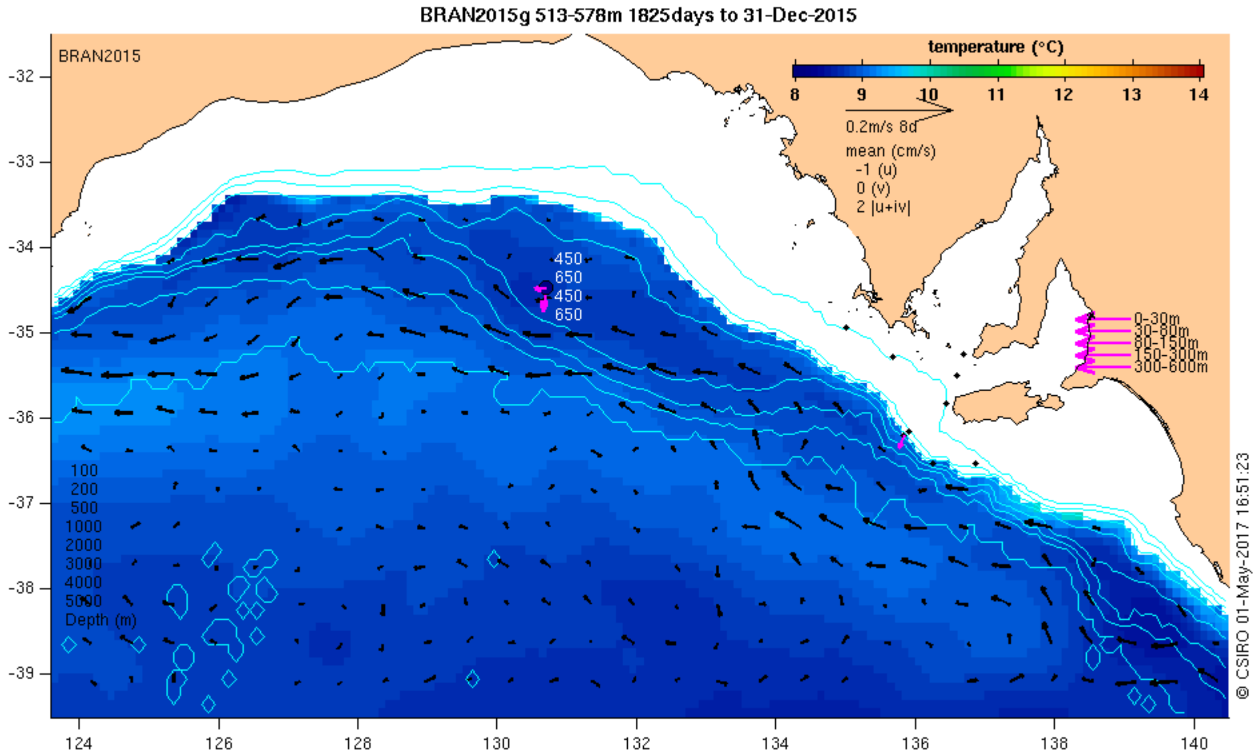

Figure 3.1.5 Five year average results (2001-2015) of the BRAN2015 global model currents at a depth of 550 m. Isobath contours (light blue) are listed on the bottom left of the figure. The location of the BP shelf mooring at 130.8 ^{o}E is indicated by the magenta dots. The colour bar is shown, Units ^{o}C.

3.1.3 Key results and discussion: mean winter circulation

Large scale current structures:

The winter average ROMS and SHOC shelf model circulation (Figure 3.1.6) were generally similar to that expected and appeared to be largely driven by winds and the eastward LC, while the BRAN2015 global model indicated a deep westward flowing FC (~ 5 10 cm/s) that is strongest in the west (Figure 3.1.5). An eastward SAC was found that is largest in the east and over the shelf break: again, the SAC may be forced by horizontal density gradients since shelf waters are lighter than those of the deep ocean.

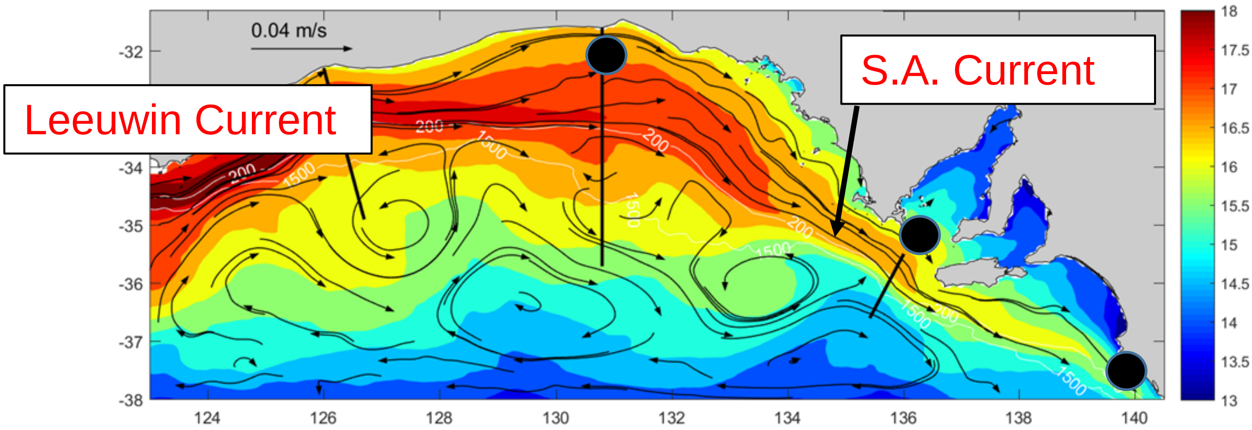

Figure 3.1.6 The plan-view of the ROMS mean winter circulation and SST. A legend vector of 0.04 m/s is shown and the colour bar at the right, Units °C. The 200 and 1500 m isobaths are shown in white. The possible sources of ammonia are indicated by the black icons ●

Leeuwin Current:

The BRAN2015 model output was used to examine the seasonal and inter-annual variability of the LC and dependency on ENSO events. In summary, the LC has a strong seasonal cycle (up to 5.5 Sv); the inter-annual variation can exceed the seasonal variation and be up to 8 Sv in some years and zero in others. The magnitude of the LC is strongly controlled by the presence of El Nino (La Nina) events that act to reduce (enhance) the magnitude of the LC.

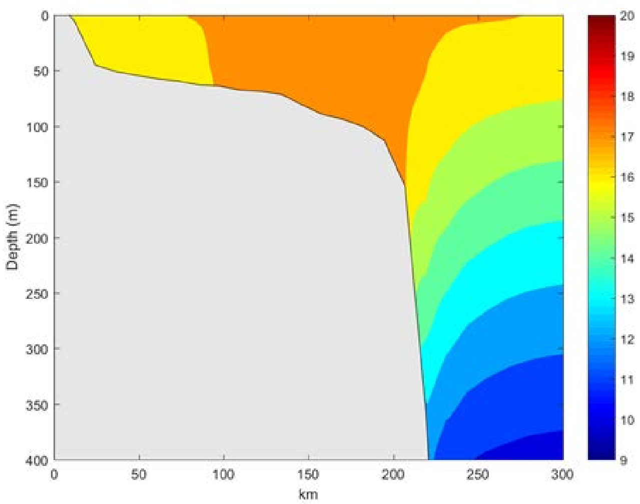

Figure 3.1.7 The mean winter temperature from ROMS over the top 400 m and for the central GAB cross section at 130.8 °E. Temperatures are indicated in the colour bars (Units °C).

Downwelling:

The winter averaged temperature from both models (e.g., Figure 3.1.7) and data exhibit downwelling to depths of 400 m across the GAB. Such downwelling is also expected to arise from both bottom boundary layer (BBL) transport of the LC and SAC and the formation of dense (cold, salty) water in the shallow coastal regions of the GAB; evaporation exceeds precipitation all year round. Indeed, in qualitative agreement with observations, the ROMS model results show the existence of relatively saline bottom water on the shelf and coastal regions of the eastern GAB and Spencer Gulf.

Upwelling:

Upwelling favourable winds can occur during winter in the eastern GAB but the water brought into the euphotic zone will be typically that which has been subject to the deep (400 m) downwelling and likely is nutrient poor. The generally eastward, shelf break LC and SAC also have BBLs that downwell water near the shelf edge.

Nutrient paths:

The waters of the LC are oligotrophic (nutrient poor) and as noted sporadic upwelling favourable winds are likely to only bring well mixed downwelled water from the shelf slope. A possible source of nutrients (e.g. NH_4) lies in the coastal formation of dense salty water that may be relatively rich in detritus. Analogous to that found for the Spencer Gulf (Middleton et al., 2013), such detritus sediments can, through microbial activity, lead to the re-mineralisation of atmospheric nitrogen and nitrates leading to a nutrient source. As the water cools during winter, it is driven from the coastal source regions, (the black icons ⬬) along the shelves and ultimately to the shelf edge and slope.

Deep thermohaline structure:

Below depths of 400 m, the modelled isotherms are generally flatter in agreement with the data. An exception here is in the far west (126 ^{o}E), (Figure 3.1.4; right panel) where the observed (and ROMS) isotherms indicate deep upwelling that may be associated with the FC expected for the region (Figure 3.1.5). Such deep upwelling is overlain by downwelling and likely not associated with shelf edge upwelling.

3.1.4 Key results and discussion: time-dependent circulation

Detailed comparisons were made between times series of model currents and the data for the 6 mooring sites shown in Figure 3.1.2. In general the agreement between the data and both SHOC and ROMS models were good to very good. An example for the NRSKAI mooring off Kangaroo Island is shown in Figure 3.1.8. The data were depth-averaged, filtered for the weather-band (3-30 days) and then resolved along the principal (major) axis. The SHOC and ROMS model output (in blue and red, respectively, are in good agreement with the data (black curve). An analysis of meteorological data shows the deep negative event on 11 June 2012 corresponds to strong south-easterly winds, while the later positive event on 15 June 2012 was driven by north westerly winds associated with an

intense low in the GAB. Notably shelf current speeds can exceed 50 cm/s and be larger than the mean seasonal fields of the LC and SAC.

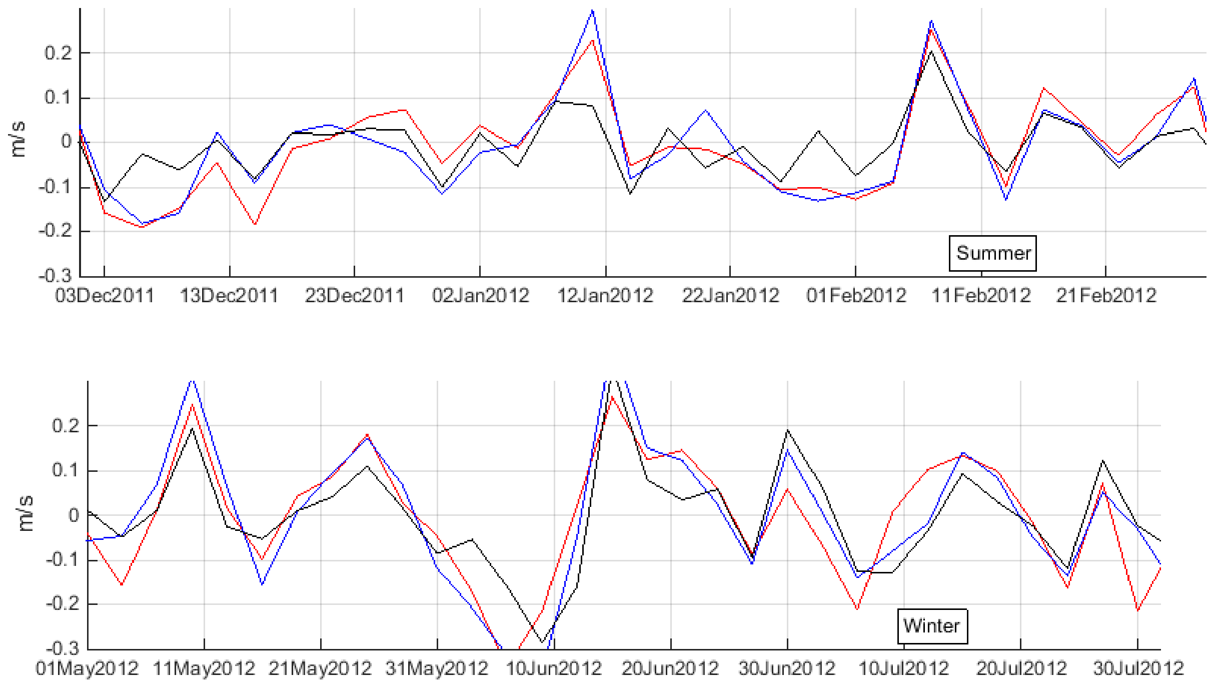

Figure 3.1.8 Weather band, vertically-averaged, major-axis velocity at NRSKAI summer (upper), and winter (lower) moorings during 2011/2012. Vertical averages were taken between the depths of the top and bottom ADCP bins. The duration of the model run is shown. Black: observations, red: ROMS, blue: SHOC.

3.1.5 Inter-annual variability of the Leeuwin Current

The inter-annual variability of the LC was determined using CSIRO's Bluelink ReANalysis (BRAN) – the global model that we also used for providing boundary conditions to our higher-resolution regional models. The benefit of BRAN is that it spans a long enough period (1993-2016) for the response to several El Nino-La Nina events to be represented.

This work showed that the volume transport of the LC varies from near-zero at one extreme to 8 Sv at the other (Figure 3.1.9). Of special interest to the GABRP is that one of these extremes occurred shortly before the GABRP *R.V. Investigator* voyage of December 2015. During the voyage, there was a conspicuous absence of a LC flowing along the shelf edge.

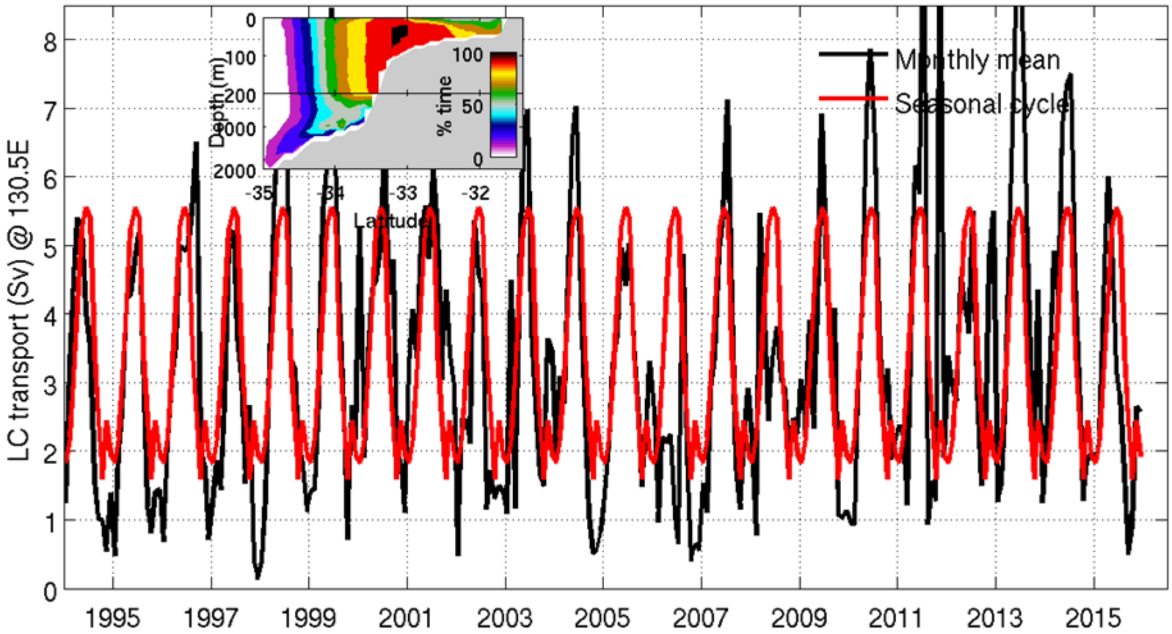

Figure 3.1.9 Time-series of the eastward transport of the LC at 130.5°E in BRAN2016. The black line shows estimates from monthly means, and the red line shows the mean seasonal cycle (based on 22 years of data, 1994-2015 inclusive). The inset shows the percentage of time that the LC was present at each grid point (100% means the LC was always present at that grid point; 50% means that the LC was present at that grid point 50% of the time, etc).

3.2 Project (1.2): Waves

3.2.1 Objectives

1. To estimate the effect of surface gravity waves (both swell and wind-waves) on
    a. surface and sub-surface transport of biota, nutrients and pollutants
    b. air-sea exchange of heat, freshwater (evaporation) and momentum
    c. turbulence throughout the water column
    d. bottom stress
2. To represent the time-dependent effects of surface gravity waves in numerical ocean circulation models.
3. To validate the improved performance of the circulation models as measured using various independent data.

3.2.2 Key results and discussion

The key result of this project was that even in a part of the world where the circulation is relatively weak but the waves are large, the influence of the waves on the circulation is not easily determined, either through modelling or from observations. This is not to say that the waves have no influence, it is only to say that the influence is difficult to detect. The strongest influence, for example, is on the near-surface (within 1 m) velocity – a quantity for which there are essentially no available field

observations. So we concluded that in order to estimate that quantity, it is an adequate approximation to estimate the Eulerian component of the surface velocity using a hydrodynamic model, then simply add an estimate of the Stokes Drift derived directly from a wave model or the wind.

4. CONTRIBUTION TO THE GABRP

The hydrodynamic model development and validation has provided a substantially more in depth and refined view of the ocean circulation and cross shelf exchange of the GAB which impact directly on other themes of the GABRP. As this theme provides *the science that underpins*, each of the contributions made is outlined below.

4.1 Theme 2: Pelagic Ecosystems

4.1.1 Ocean colour acquisition and validation

Many data on the Australian Ocean Data Network (AODN) websites are in a format called NetCDF rather than more commonly used formats such as Microsoft Excel. Thus, the purpose of the report below is to enable such users and other GABRP themes to readily obtain such data and in particular, satellite derived Ocean Colour and SST data. The following report was produced:

Redondo Rodriguez, A., Middleton, J. F., and R. Proctor (2015): Accessing IMOS Satellite data into csv format, from the IMOS Portal. GAB Res. Project report. – a tutorial available at imos.aodn.org.au and at http://www.misa.net.au/GAB/research_results/reports

In collaboration with Edward King (IMOS Satellite Remote Sensing Facility; imos.org.au), a detailed analysis of remote sensed and *in-situ* observations of ocean colour data has been made. Two reports were produced:

Redondo Rodriguez, A., King, E. and M. Doubell, (2015a): Validation of MODIS imagery in the Great Australian Bight, GAB Res. Project report.
http://www.misa.net.au/GAB/research_results/reports

Redondo Rodriguez, A., King, E. and M. Doubell (2015b): Regional variability of MODIS imagery in the Great Australian Bight., GAB Res. Project report.
http://www.misa.net.au/GAB/research_results/reports

The reports summarise the expected data availability and accuracy of three Moderate Imaging spectro-radiometer (MODIS) products (SST, chlorophyll-*a* and euphotic depth) and their algorithms. There was not enough *in situ* data to produce an improved algorithm, but the best algorithms for the GAB were identified in these reports, as well as the expected accuracy and limitations of the different products. These reports and the tutorial have been disseminated to the other themes.

4.1.2 Nutrient pathways to the shelf edge of the central GAB

Several sets of numerical experiments and analyses were undertaken for Theme 2 to examine possible paths of nutrient supply in the central GAB.

First, a set of general particle tracking experiments were undertaken using ROMS as part of those needed to establish general connectivity for the GAB. In conclusion, nutrient rich water upwelled in the eastern GAB has no direct path to the shelf edge of the central GAB. Pathways of transport were found from the western GAB which might supply nutrients, although upwelling in the far west seems small.

Second, a set of nutrient dispersal studies using ROMS was done for each summer season (January) of 2011, 2012, 2013 and 2014. The observed distribution of nitrate concentrations off the shelf slope (depths to 1300 m) and at the central GAB section 130.8 ^{o}E were adopted and realistic simulations undertaken to see if the known downwelling could act to mix nitrates from depths of 300 m to the shelf edge (~100 m). The results for the downwelling is expected to dominate with little vertical mixing of nutrients. It is noted that convective overturning is not modelled by ROMS (or most hydrodynamic models) which make the hydrostatic assumption. Thus, convective overturning may be a mechanism for nutrient supply from deep waters.

Results for these studies are presented in Theme 2, Project 2.2: Characterise spatial variability of offshore/slope plankton, and micronekton communities.

Based on the modelling undertaken here and the related studies by Middleton and Leth (2004) Middleton et al. (2014) and Richardson (2014) the likely nutrient paths were identified above.

4.1.3 Analyses of tagged sea lion data

Two analyses of tagged sea-lion conductivity, temperature and depth (CTD) data were made available to Theme 2 so as to determine a) possible errors in both positional fixes and salinity observations and b) the water mass (T/S) properties of the central and eastern GAB and expected oceanic transport patterns.

Results for these studies are presented in Theme 2 and notably through the work: F. Bailleul, L. Richardson, P. Van Ruth, C. R. McMahon, R. G. Harcourt, J. F. Middleton, T. Ward, S. D. Goldsworthy (2017) Animal-borne instruments provide new observations of seasonal subsurface oceanographic features over the continental shelf of the Great Australian Bight.

4.2 Theme 3: Benthic Biodiversity

Annual averaged and maximum values of bottom stress magnitude were considered to be the most appropriate oceanographic parameters to influence the benthos. To this end, bottom stress from ROMS was averaged over a two year model simulation (2013-2014) and the mean and maxima values stored. These were used as one of a suite of environmental covariates in the analysis of infaunal and epifaunal data in Theme 3, to determine what variables may be influencing patterns of infaunal and epifaunal community structure.

4.3 Theme 4: Ecology of Iconic Species and Apex Predators

Theme 4 aims to determine areas of ecological significance for iconic species and apex predators or mean preferred foraging regions and associated physical drivers. The investigators planned to use

Time Spent by Sector (TPS) analyses to identify such areas which were to be compared with physical information from Theme 1.

4.4 Theme 5: Petroleum Geology and Geochemistry

Tarballs behave as surface drifters and are influenced by both Stokes and wind drift. Asphaltites are neutrally buoyant and less effected by Stokes and wind drift. To assist in understanding the possible origins of these petroleum products three sets of particle tracking studies were undertaken and the information provided to Theme 5. These were:

1) The general connectivity studies conducted using ROMS and detailed above. These were forward tracking studies of neutrally buoyant particle: a proxy for asphaltites.
2) A second set of ROMS studies with the origins of particles assumed known or using suspected sites of deep water hydrocarbon seepage.
3) Backward tracking studies of tarballs were conducted using the global BRAN model and Wavewatch III estimates of surface Stokes drift from Theme 1 Project 1.2.

Results for these studies allowed for the determination of likely origins of asphaltites and tarballs.

4.5 Theme 7.1: Integration and Modelling

Twelve hour to three day averages of the model outputs for the four years (2011 to 2014) were needed by Theme 7.

These were utilised to generate forcing files for the ecosystem models. The forcing fields were calculated by taking exchanges between boxes from the current flows in the hydrodynamic models.

4.6 Final Comments

What did we learn about the GAB that we did not know previously and why is this knowledge important?

The analyses of the hydrodynamic models and data have for the first time provided a holistic view of the ocean circulation of the GAB and at a resolution that enables the major current systems (CC, LC, SAC and FC) to be well resolved, including those for cross-shelf exchange which are found to support nutrient paths in the eastern GAB during summer but year-round downwelling in the central GAB. This result was foreshadowed by Middleton and Platov (2003) but using a crude model of the region. The analysis of the global BRAN2015 model demonstrated the likely existence of the FC at depths of 500 m or more with indirect support coming from other observations, including sea glider data and the water mass analyses of Richardson (2015). This demonstrated the existence of a westward "conveyor belt" with speeds of 5 cm/s (or 1500 km/year) that can move material from the central GAB towards the west.

What are the knowledge and data gaps and what are the priorities for future research for this Theme?

The key gaps and priorities identified were:

a) The nature and role of the deep mesoscale eddy field was not well modelled by the ROMS and SHOC shelf models. Possibly, data assimilating models might better resolve such eddies.

b) The relative importance of the forcing mechanisms for the regional circulation including, winds, boundary inflows (e.g., LC), initial T/S fields and role of density fields: the latter are dependent on the T/S field adopted but also estimates of atmospheric heat and freshwater fluxes that are typically less accurate than those for momentum.

What are the Theme outputs and outcomes?

Outputs include:

a) The development of two (ROMS and SHOC) models for the GAB.
b) Improved algorithms and accessibility to Ocean Colour data.
c) Information for other themes.

Outcomes include:

a) A better understanding and quantitative estimation of the major current features of the region and nutrients paths for both summer and winter.
b) Other GABRP themes better informed of oceanography and possible impact.

5. CONCLUSION

The GAB is characterised by a deep ocean FC, nearshore CC and shelf edge LC and SAC. These current systems have typical magnitudes of 5 – 25 cm/s that are relatively small compared to the other major current systems around the Australian continent (e.g., East Australian Current). Nonetheless, over a season, such currents can transport particulate matter and marine biota over distances of 390 km to 2000 km. Shelf and shelf edge currents within the GAB are also generally seasonal in nature (in keeping with the atmospheric forcing), with the notable exception of the eastward SAC. The existence of the SAC during summer has been ascribed to sea level gradients (Middleton and Platov, 2003) that arise from the “collision” of Sverdrup transports in the central GAB and at the shelf edge. However, its existence off Kangaroo Island suggests that other mechanisms such as thermohaline forcing may be important; the differences in temperature (and density) between the shelf and deep ocean may lead to pressure forces that drive the SAC and other aspects of the GAB shelf circulation. The importance of such forcing compared to that of winds remains a knowledge gap to be addressed in future studies.

Downwelling was found to occur all year round in the central GAB; in winter driven by atmospheric cooling and evaporation, while in summer, driven by the “collision” of Sverdrup transports in the central GAB. This downwelling is important to nutrient paths which for the first time have been identified for the GAB based on the analysis here and the related studies by Middleton et al. (2014) and Richardson (2015).

For summer, the upwelling in the eastern GAB is enhanced by the existence of submarine valleys and headlands which draw nutrient rich water (e.g., nitrates) from depths of 150 m or more along the Bonney Coast and Kangaroo Island regions: this water is transported to the west coast of the Eyre Peninsula. In the far western GAB, SST observations and theory (adapted from Middleton and Leth 2004), indicate wind-forced upwelling to be largely shut down. In the central GAB the year-round downwelling would seem likely to preclude upwelling, although other mechanisms such as double diffusion and convective overturning may be important for vertical fluxes of nutrients.

During winter, atmospheric cooling and evaporation create cold dense water that ultimately is expelled off the shelf and into the 200 - 250 m deep waters of the shelf break. This water may contain high levels of detritus, sediments and ammonia. In analogy with Spencer Gulf (Middleton et al., 2013) we speculate that ammonia in this detritus might be re-mineralised into atmospheric nitrogen and nitrates.

The above indicates that wind-forced upwelling occurs on a seasonal basis. More precisely it is associated with summertime south-easterly wind events that can act for 5-10 days and occur 4-5 times during each summer. Similarly, during winter the passage of intense low pressure systems can cool coastal water and drive very strong shelf currents that may trigger offshore flows of cold, dense coastal waters.

The GAB is known for its large waves and strong winds. We investigated the impact that the waves have on the circulation, thinking that the relative importance of the waves would be large here, given that the circulation is generally quite weak. We found that while the Stokes Drift at the surface is theoretically very important for the transport of material at the surface, we could not conclusively demonstrate that this was the case, largely for the lack of empirical evidence, but also because modelling studies gave mixed results. Nor could we demonstrate that there was a measurable benefit from dynamically coupling a wave model with a circulation model: a circulation model forced only by winds gives essentially the same results (as long as the average effects of waves are suitably parameterized).

In conclusion, the modelling and data analyses conducted have revealed the GAB and environs to host quite complex and unique current systems and mechanisms for cross-shelf exchange. As shown these have implications for nutrient paths which underpin the ecosystem of the region.

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