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Mesoscale features create hotspots of carbon uptake in the Antarctic Circumpolar Current

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ABSTRACT

The influence of eddy structures on the seasonal depletion of dissolved inorganic carbon (DIC) and carbon dioxide (CO_2) disequilibrium was investigated during a trans-Atlantic crossing of the Antarctic Circumpolar Current (ACC) in austral summer 2012. The Georgia Basin, downstream of the island of South Georgia (54-55°S, 36-38°W) is a highly dynamic region due to the mesoscale activity associated with the flow of the Subantarctic Front (SAF) and Polar Front (PF). Satellite sea-surface height and chlorophyll-a anomalies revealed a cyclonic cold core that dominated the northern Georgia Basin that was formed from a large meander of the PF. Warmer waters influenced by the SAF formed a smaller anticyclonic structure to the east of the basin. Both the cold core and warm core eddy structures were hotspots of carbon uptake relative to the rest of the ACC section during austral summer. This was most amplified in the cold core where greatest CO_2 undersaturation (-78 μatm) and substantial surface ocean DIC deficit (5.1 mol m^{-2}) occurred. In the presence of high wind speeds, the cold core eddy acted as a strong sink for atmospheric CO_2 of 25.5 mmol m^{-2} day^{-1}. Waters of the warm core displayed characteristics of the Polar Frontal Zone (PFZ), with warmer upper ocean waters and enhanced CO_2 undersaturation (-59 μatm) and depletion of DIC (4.9mol m^{-2}). A proposed mechanism for the enhanced carbon uptake across both eddy structures is based on the Ekman eddy pumping theory: (i) the cold core is seeded with productive (high chlorophyll-a) waters from the Antarctic Zone and sustained biological productivity through upwelled nutrient supply that counteracts DIC inputs from deep waters; (ii) horizontal entrainment of low-DIC surface waters (biological uptake) from the PFZ downwell within the warm core and cause relative DIC-depletion in the upper water column. The observations suggest that the formation and northward propagation of cold core eddies in the region of the PF could project low-DIC waters towards the site of Antarctic Intermediate Water formation and enhance CO_2 drawdown into the deep ocean.

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1. Introduction

The Southern Ocean is a key component in the global meridional overturning circulation through water mass formation, ventilation, and transport by the Antarctic Circumpolar Current (ACC) between the Atlantic, Pacific and Indian ocean basins (Marshall and Speer, 2012). The ACC is predominantly driven by strong westerly winds where shoaling isopycnal surfaces towards the Antarctic continent enable a direct connection between the surface and the deep ocean and the transfer of carbon dioxide (CO_2) to the ocean interior (Rintoul et al., 2001; Watson and Orr, 2003; Hauck et al., 2013). The ACC is characterized by a series of circumpolar fronts that are distinguished by strong meridional gradients in hydrographic and biogeochemical parameters (Orsi et al., 1995; Pollard et al., 2002);

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the Sub-Tropical Front (STF), the Subantarctic Front (SAF), Polar Front (PF), the Southern ACC Front (SACCF) and the Southern Boundary (SB). Between the STF and SAF are the sub-tropical waters of the Sub-Antarctic Zone (SAZ). The SAF and the PF delimit the sub-Antarctic waters of the Polar Frontal Zone (PFZ). South of the PF is the Antarctic Zone (AAZ). Inverse modelling suggests that the CO_2 sink of the Southern Ocean is sensitive to climate change as wind intensification can lead to increased upwelling of deep waters rich in natural CO_2 (Le Quéré et al., 2007; Law et al., 2008; Lovenduski et al. (2008); Zickfeld et al., 2008). In contrast, hydrographic data indicates that transport and meridional overturning circulation in the ACC is not very sensitive to increasing winds (Böning et al., 2008) due to mesoscale (principally eddy) activity in the ACC being inadequately resolved by numerical simulations. Hence gaps persist in the understanding of the role of eddies on CO_2 uptake in the ACC.

Mesoscale structures, such as meandering hydrographic fronts, currents, eddies and topographically induced turbulence, are ubiquitous in the ACC. Such structures are linked to enhanced entrainment, retention, mixing, biological production and transport of heat, salt, carbon and nutrients within the ACC (McGillicuddy and Robinson, 1997; Siegel et al., 1999). Mesoscale eddies are conspicuous structures, typically up to 50 km in radius (of the order of the first baroclinic Rossby radius), and can be detected by anomalies in sea surface height and temperature. Eddies contribute to distinct patchiness in the upper ocean by affecting the spatio-temporal distribution of sea surface chlorophyll-a and productivity of phytoplankton through the uplift or subduction of isopycnals and nutriclines (Strass, 1992; Kimura et al., 1997; McGillicuddy et al., 1998; Lee and Williams, 2000; Lévy, 2003; Klein and Lepeyre, 2009; Saraceno and Provost, 2012) and they play an important role in the ACC component of the global overturning circulation (Thompson et al., 2014). The concept of 'eddy pumping' states that vertical motions within the eddy cores produces anomalies in sea surface height and temperature (McGillicuddy et al., 1998; Klein and Lapeyre, 2009). Cold core (cyclonic) eddies lead to a doming of isopycnals and upwell cold, nutrient-rich deep water into the euphotic zone (McGillicuddy and Robinson, 1997). Cold core eddies can be detected by satellite as negative sea surface height and are often associated with increased biological productivity (Falkowski et al., 1991; Robinson et al., 1993; Allen et al., 1996; McGillicuddy et al., 1998). Warm core (anticyclonic) eddies can be detected by an elevated sea surface height (positive sea level anomaly) and are vortices of anticlockwise rotating water leading to a deepening of isopycnals and downwelling of surface waters, which are relatively unproductive (McGillicuddy and Robinson, 1997; McGillicuddy et al., 1998). However, other mechanisms such as deepening mixed layers and horizontal advection can result in productive anticyclonic eddies (Dufois et al., 2014). The objective of this study is to understand the role of eddies on the biological carbon uptake in the ACC (e.g., Moore and Abbott, 2000; Strass et al., 2002; Sokolov and Rintoul, 2007; Le Quéré et al., 2007; Böning et al., 2008) and the wider impact of eddies on the sensitivity of the carbon cycle to climate change in the Southern Ocean.

Remotely sensed chlorophyll-a and sea surface height showed high levels of mesoscale activity downstream (to the north) of the island of South Georgia (54-55°S, 36-38°W) in the Atlantic sector of the Southern Ocean (Korb et al., 2004; Borrione and Schlitzer, 2013). Shipboard surveys have revealed finer scale topographic interactions of the SAF, PF and SACCF with the Scotia Ridge that leads to meandering and the formation of eddy structures in the Georgia Basin (Trathan et al., 1997; Meredith et al., 2003; Korb and Whitehouse, 2004; Smith et al., 2010). The waters in the Georgia Basin support vast phytoplankton blooms that develop each year and often persist for 04 months or more, characterising the region as one of the most biologically productive areas in the Southern Ocean (Atkinson et al., 2000; Korb and Whitehouse, 2004; Korb et al., 2004; Borrione and Schlitzer, 2013). Enhanced biological uptake of CO_2 occurs from spring to summer to autumn in the large South Georgia blooms (Jones et al., 2012, 2015; Jones et al., in press).

Persisting mesoscale activity and eddy formation mechanisms associated with the meandering of the PF and SAF make the Georgia Basin an ideal location to explore the effects of eddy dynamics on the uptake and cycling of CO_2 in the ACC. Anomalies in remotely sensed sea surface topography and chlorophyll-a in austral summer 2012 revealed the presence of an eddy dipole structure downstream of South Georgia. Shipboard hydrographic measurements confirmed the existence of a large (~400 km diameter) cyclonic cold core in the northern Georgia Basin with warmer waters to the east forming a smaller anticyclonic core (Strass et al., 2017). Effects of the mesoscale eddy structures on the seasonal depletion of inorganic carbon and the summertime CO_2 disequilibrium are investigated. The data comprise shipboard continuous and discrete measurements of the CO_2 system and MODIS-Aqua ocean colour and altimetry data. Results from these measurements are put into context by reference to the whole trans-Atlantic passage and the potential of eddies to create 'hotspots' of carbon uptake in the ACC is inferred.

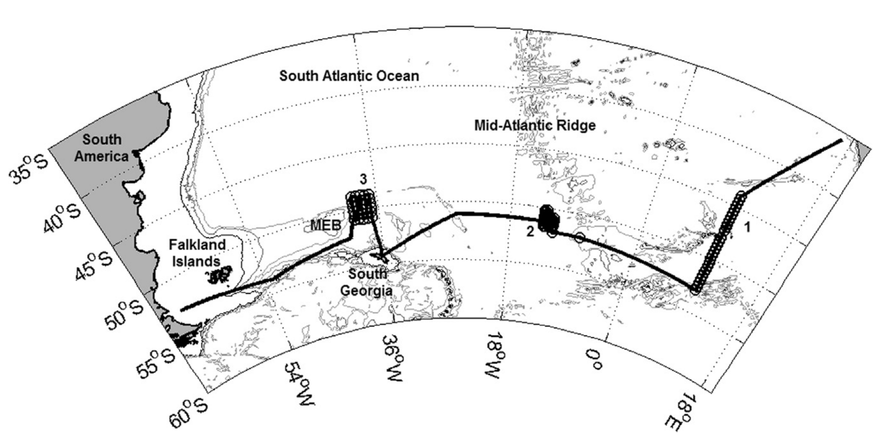

Fig. 1. Map of the ANT-XXVIII/3 cruise track in the South Atlantic and Southern Ocean. The surveyed regions are depicted by clusters of hydrographic stations (black open circles) and labelled numerically as: (1) a section along 44-53°S, 10°E (stations 57–84); (2) mesoscale survey at 50-52°S, 12-13.5°W west of the Mid-Atlantic Ridge (stations 87–142); (3) mesoscale survey at 48.5-51.5°S, 37-39.5°W in the Georgia Basin (stations 144–173). South Georgia island, Mid-Atlantic Ridge, Maurice-Ewing Bank (MEB) and the Falkland Islands are marked on the map.

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