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Modification of deep waters in Marguerite Bay, western Antarctic Peninsula, caused by topographic overflows

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ABSTRACT

Circumpolar Deep Water (CDW) intrudes from the mid-layers of the Antarctic Circumpolar Current onto the shelf of the western Antarctic Peninsula, providing a source of heat and nutrients to the regional ocean. It is well known that CDW is modified as it flows across the shelf, but the mechanisms responsible for this are not fully known. Here, data from underwater gliders with high spatial resolution are used to demonstrate the importance of detailed bathymetry in inducing multiple local mixing events. Clear evidence for overflows is observed in the glider data as water flows along a deep channel with multiple transverse ridges. The ridges block the densest waters, with overflowing water descending several hundred metres to fill subsequent basins. This vertical flow leads to entrainment of overlying colder and fresher water in localised mixing events. Initially this process leads to an increase in bottom temperatures due to the temperature maximum waters descending to greater depths. After several ridges, however, the mixing is sufficient to remove the temperature maximum completely and the entrainment of colder thermocline waters to depth reduces the bottom temperature, to approximately the same as in the source region of Marguerite Trough. Similarly, it is shown that deep waters of Palmer Deep are warmer than at the same depth at the shelf break. The exact details of the transformations observed are heavily dependent on the local bathymetry and water column structure, but glacially-carved troughs and shallow sills are a common feature of the bathymetry of polar shelves, and these types of processes may be a factor in determining the hydrographic conditions close to the coast across a wider area.

1. Introduction

The flow of Circumpolar Deep Water (CDW) onto and across the continental shelf along the western Antarctic Peninsula (WAP) is key to understanding the heat flux reaching floating ice sheets and glaciers. This water mass originates in the mid-layers of the Antarctic Circumpolar Current (ACC), the southernmost parts of which lie adjacent to the continental slope in the vicinity of the WAP. Having intruded onto the shelf, a modified version of CDW is created (mCDW) through a combination of mixing, heat loss to the atmosphere (Turner et al., 2013) and ice formation and melt, with each process having different spatial and temporal patterns (Martinson et al., 2008). Satellite measurements show that the WAP glaciers are generally thinning rapidly (Pritchard et al., 2009), concurrent with a retreat in most valley glaciers along the Peninsula (Cook et al., 2005), with both processes contributing to global sea level rise. Despite recent warming (Turner et al., 2005), atmospheric-driven melting and iceberg calving appear insufficient to explain the rates of melt observed, while the heat content in mCDW suggests a likely source of the energy, however sufficiently accurate estimates of ocean heat flux in the area are presently lacking (Pritchard et al., 2012; Rignot et al., 2013) though a warming trend has been observed in this water mass (Schmidtko et al., 2014).

Several mechanisms have been proposed for the flow of CDW onto the shelf, involving crossing the physical and dynamical barrier of the steep shelf break. These include direct flow into canyon mouths, eddy shedding, flow-topography interactions where the shelf-break curves strongly and Ekman induced upwelling (Klinck and Dinniman, 2010; Martinson and McKee, 2012; Moffat et al., 2009). Deep canyons that dissect the WAP shelf are filled with mCDW and, due to their enclosed basins have slow currents. Above this deep layer, the circulation is less constrained by bathymetry and is complex and time-varying, though there have been indications of a system of gyres separating the northeastward flow at the shelf-break from a general southward flow close to land. This latter circulation feature is associated with seasonal wind forcing and density gradients associated with enhanced freshwater inputs (Moffat et al., 2008). Consideration of isotopic tracer data has revealed that these freshwater inputs are predominantly from meteoric sources (glacial melt and precipitation) (Meredith et al., 2013).

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As well as glacial ice, there have also been considerable changes to sea ice in Antarctica. A small but significant circumpolar increase in sea ice is the result of large, counteracting regional gains and losses (Holland and Kwok, 2012). For the WAP shelf, the sea-ice season has shortened considerably (Stammerjohn et al., 2008a) such that the sea surface is exposed to the atmosphere for longer. Significant changes are seen in the winter mixed-layer depth and summer stratification, heat uptake and seasonal thermocline depth in the Rothera Time Series (RATS) following variations in winter sea-ice cover (Venables and Meredith, 2014), demonstrating the sensitivity of the ocean structure to such climatic changes.

The bathymetry in Marguerite Bay is the result of erosion and deposition during glacial periods when sea levels were lower and the Antarctic continental ice field more extensive (Livingstone et al., 2013). Marguerite Trough is an important bathymetric feature, providing a route for CDW to flow onto the shelf and into Marguerite Bay (Klinck et al., 2004). Another feature of the glacial geomorphology on the shelf is the presence of overdeepened depressions with shallow sills. These present a barrier to flow across the shelf, potentially making the cross-shelf flow sensitive to shoaling of isotherms or changes to sea level.

The focus of this study is flow/bathymetry interactions over sills and within enclosed topographic depressions, which we show to be important in causing water mass modification. We identify key locations where significant vertical flows and mixing occurs, which are important in determining how mCDW escapes the deep troughs and interacts with the bathymetry and overlying waters. We also present data for enclosed depressions south of Adelaide Island where the shallow sills lead to cold bottom temperatures and Palmer Deep, which is warmer at depth than other locations along the shelf. We use high-resolution hydrographic data collected by autonomous Slocum gliders over three seasons together with hydrographic data from a short research cruise and data from an oceanographic/biogeochemical time series conducted close to Rothera Research Station in northern Marguerite Bay.

2. Methods and data

Data were collected using deep (1000 m rated) Slocum ocean gliders. These were instrumented with a pumped CTD (Conductivity, Temperature, Depth) unit, plus sensors for chlorophyll and turbidity. The glider altimeters allowed sampling to within 20 m of the seabed through the deployments. Data used here are from gliders deployed and recovered at the British Antarctic Survey base at Rothera in the 2012/13 and 2013/14 seasons, and a third launched from the RRS *James Clark Ross* in the 2015/16 season in transit to Rothera, which was flown to the United States' Palmer Station (Fig. 1). At the time of writing, only low-resolution data transmitted over Iridium satellite are available from this latter glider.

The temperature and salinity values from the Rothera-launched gliders were compared against a concurrent cast in Ryder Bay collected using an SBE19 CTD as part of the Rothera Oceanographic Time Series (RATS). The glider profiles extend deeper than 400 m, beyond than the 350 m deep sill that separates Ryder Bay from the ocean beyond, thus ensuring stability of the deep water mass used for intercomparison purposes. Although slight differences (≈0.01 °C and 0.001 in salinity) were detected, there was no drift on any deployment and no adjustments have been made.

The RATS instruments are rotated for servicing and calibration every two seasons, and data are compared against the ARSV *Laurence M. Gould*'s SBE911 CTD each summer on casts taken inside and outside Ryder Bay. During these comparisons, the RATS CTD(s) are fixed to the larger frame on the ARSV *Laurence M. Gould*, one metre above the ship's instruments. This, together with weekly collection of discrete salinity samples for calibration purposes, leads to a series of time-dependent calibrations for each instrument's duration at Rothera (Clarke et al., 2008; Venables et al., 2013) as well as joint casts between the two RATS CTDs in summers when they are swapped round, further ensuring consistency through the time series.

The gliders deployed from Rothera occupied their sections twice, once on the outbound journey from the base, and once on their return, and extremely good agreement was found between the two legs.To investigate possibly hysteresis, glider data were compared between upward and subsequent downward dives while the vehicles held station. There was a very slight systematic offset between up and down casts, matching changing gradients in the temperature profile, peaking at 3×10^{-3} °C, or about 10 cm offset on each of the profiles. As this effect is small compared with the natural variability caused by e.g. internal waves (± 0.3 °C) and to the effects studied, both up and down casts are used here, with no correction applied.

A follow-up cruise, designated JR307, was undertaken to the enclosed depressions south of Adelaide Island between 31 December 2014 and 7 January 2015. This involved CTD casts, water samples for biogeochemical measurements, and benthic biology sampling inside and outside of the cold holes (Fig. 2). The physical data are presented here, using calibrations obtained during a CTD transect across Drake Passage immediately afterwards (King and Firing, 2015).

Bathymetry data used were the 15-s resolution Southern Ocean Global Ocean Ecosystems Dynamics (SO GLOBEC) compilation (Bolmer et al., 2004) and, for Palmer Deep area, the International Bathymetric Chart of the Southern Ocean (IBCSO) version 1.0 (Arndt et al., 2013).

3. Results

3.1. Bathymetric setting

The main glider track from Jan/Feb 2014 follows a channel linking Marguerite Trough and Laubeuf Fjord, the deep trough that feeds into Ryder Bay (Fig. 1). This channel is the only deep connection between the troughs. Swath bathymetry maps show a series of transverse ridges across the channel. As detailed below, the deep water flows from Marguerite Trough to Laubeuf Fjord and the ridges block the densest water and lead to localised mixing between mCDW and overflowing water. There are no other deep routes connecting Laubeuf Fjord with Marguerite Trough so the return flow must be at shallower depths. This pattern of overdeepened depressions and sills is common across the WAP shelf due to its glacial history and a similar pattern is found near Anvers Island. The details are inevitably different in each location but the processes described are repeatable across a wide area.

3.2. Blocking and overflows

It is evident from the salinity profiles (Fig. 3d) that the densest waters are blocked by the ridge (note that in the temperature and depth range of this study, salinity is the dominant control on density, hence only salinity is shown, with density profiles looking almost identical in form). There is a step change in near-bottom salinity of 0.005 after the first ridge (Fig. 3a). The downstream cavity must therefore be filled by water from shallower depths that overflow the sill, and which subsequently descend by 300–500 m. This process is repeated at several ridges along the length of the channel, each time creating a step change in deep salinity. The overall reduction in salinity is approximately 0.06 by the end of the section.

Initially the water column has a well-structured temperature profile typical of the Southern Ocean, with a temperature maximum > 1.4 °C at 300–400 m with temperatures reducing slightly with depth to the bottom, and reducing rapidly at shallower depths to a temperature minimum comprising Winter Water (WW), the remnant of the upper-ocean winter mixed layer (Figs. 3c, 4b). After the first two ridges the near-bottom temperature increases by 0.05 °C. This can only happen by a downward flow of water from close to the temperature maximum as water flows over a sill into the basin. Lateral advection of warmer