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Controls on turbulent mixing on the West Antarctic Peninsula shelf

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ABSTRACT

The ocean-to-atmosphere heat budget of the West Antarctic Peninsula is controlled in part by the upward flux of heat from the warm Circumpolar Deep Water (CDW) layer that resides below ~200 m to the Antarctic Surface Water (AASW), a water mass which varies strongly on a seasonal basis. Upwelling and mixing of CDW influence the formation of sea ice in the region and affect biological productivity and functioning of the ecosystem through their delivery of nutrients. In this study, 2.5-year time series of both Acoustic Doppler Current Profiler (ADCP) and conductivity-temperature-depth (CTD) data are used to quantify both the diapycnal diffusivity κ and the vertical heat flux Q at the interface between CDW and AASW. Over the period of the study, a mean upward heat flux of ~1 W m^{-2} is estimated, with the largest heat fluxes occurring shortly after the loss of winter fast ice when the water column is first exposed to wind stress without being strongly stratified by salinity. Differences in mixing mechanisms between winter and summer seasons are investigated. Whilst tidally-driven mixing at the study site occurs year-round, but is likely to be relatively weak, a strong increase in counterclockwise-polarized near-inertial energy (and shear) is observed during the fast-ice-free season, suggesting that the direct impact of storms on the ocean surface is responsible for much of the observed mixing at the site. Given the rapid reduction in sea-ice duration in this region in the last 30 years, a shift towards an increasingly wind-dominated mixing regime may be taking place.

1. Introduction

The intrusion of warm, saline water masses onto polar ocean shelves is believed to be an important pathway for the delivery of heat to the base of glaciers and/or ice shelves (e.g. Straneo et al., 2012; Martinson and McKee, 2012; Inall et al., 2014). In the Antarctic, relatively warm and unmodified Circumpolar Deep Water (CDW) floods onto the West Antarctic Peninsula (WAP) shelf below 200 m, particularly in the vicinity of deep, glacially-scoured troughs such as the Marguerite Trough (Fig. 1). Several studies point to eddy shedding, topographic steering and Ekman processes as being likely candidates for fluxing this water mass landward from the Antarctic Circumpolar Current (ACC) (Moffat et al., 2009; Klinck and Dinniman, 2010). However, the heat budget of the shelf itself is not well constrained, with estimates of both lateral and vertical heat fluxes being poorly quantified. These fluxes strongly control the interaction between the CDW and the overlying Antarctic Surface Water (AASW), which in turn can affect the volume of seasonal sea ice formed and the heat ultimately delivered to the atmosphere (Valkonen et al., 2008) and cryosphere (Pritchard et al., 2012; Rignot et al., 2013).

The WAP and its surrounding ice shelves (Fig. 1a) are undergoing rapid changes in environmental conditions, driven by forcing that includes atmospheric warming (Turner et al., 2005) and increased wind stresses (Marshall, 2003; Stammerjohn et al., 2008a). Stronger winds, believed to be associated with a positive phase of the Southern Annular Mode (SAM), have been linked to reduced thickness and longevity of sea-ice cover (Stammerjohn et al., 2008b). In addition, rapid summertime warming of the upper 100 m of the water column has been observed (Meredith and King, 2005) and over 80% of the glaciers on the WAP shelf are retreating, with retreat rates increasing (Cook et al., 2005, 2014).

Recent evidence from both the Arctic and Antarctic suggest that these oceanographic and sea-ice changes have the potential to change significantly the diapycnal mixing of heat, salt and nutrients on polar ocean continental shelves. For instance, loss of sea ice in the Arctic has been linked to stronger mixing across the base of the

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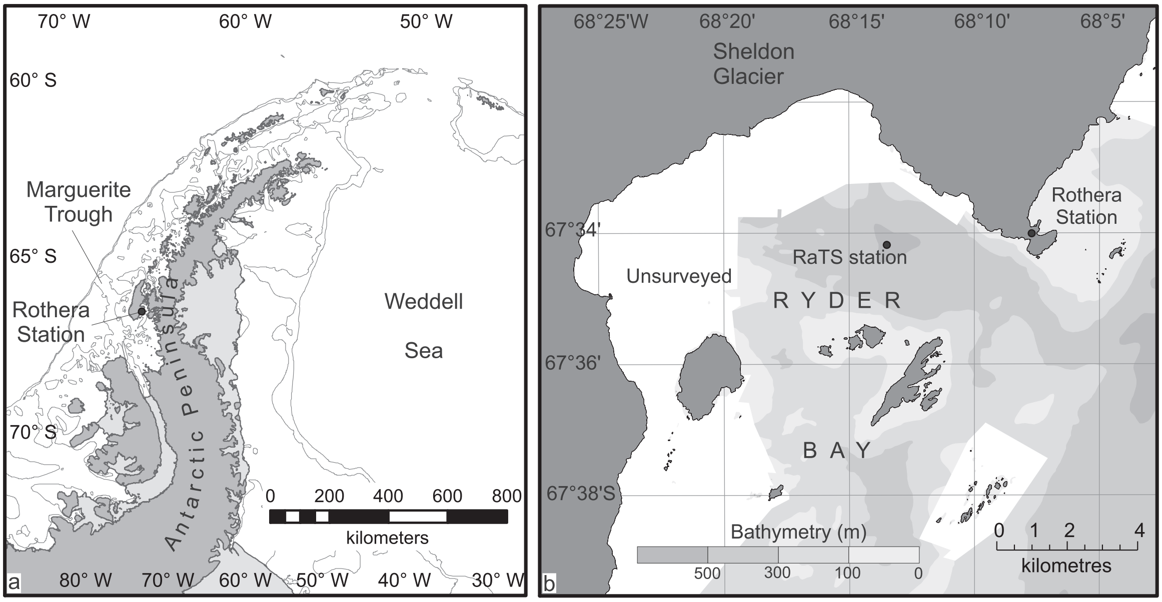

Fig. 1. (a) Location of Rothera station on the West Antarctic Peninsula shelf, with Marguerite Trough indicated. 500 m and 1000 m isobaths from the International Bathymetric Chart of the Southern Ocean (IBCSO) are indicated; (b) Position of the RaTS mooring within Ryder Bay. The location of the British Antarctic Survey base at Rothera, from which the meteorological and ice observations were collected, is marked. The CTD measurements, acquired at roughly two-week intervals, were made as close as practicable to the mooring location (see Venables et al. (2013)). Bathymetry is indicated.

pycnocline through the input of near-inertial shear (Rainville and Woodgate, 2009). Hyatt et al. (2011) postulate that sea ice within Marguerite Bay on the WAP continental shelf acts as both a thermal and mechanical barrier during winter, reducing diapycnal mixing. In addition, a change in near-surface stratification associated with an increase in the length of the fast-ice-free season may also affect mean values of diapycnal diffusivity κ. This can occur either by a reduction in the value of N^2 in the Osborn equation (which translates turbulent kinetic energy dissipation, ε, into diffusivity κ) (Osborn, 1980), or through the impact of changing stratification on internal tides, which have been identified as being important farther north on the South Scotia Ridge (Padman et al., 2006) and on the continental shelf itself (Wallace et al., 2008). These changes in diapycnal mixing have the potential to feed back on the volume of sea ice produced (for example increased upward heat fluxes could reduce further the volume of sea ice, or reduced albedo could increase the summer heat content of the ocean). Such changes could lead to large shifts in both upper ocean heat and salt properties and in air-sea fluxes; however the complex web of feedbacks remains insufficiently understood.

This paper uses a time series of co-located moored current velocity and conductivity-temperature-depth (CTD) measurements collected in Ryder Bay (Fig. 1b) between January 2005 and May 2007 to investigate variability in turbulent diffusivity and vertical heat fluxes over 2.5 years. Background information about the measurements is given in Clarke et al. (2008), Meredith et al. (2010) and Venables et al. (2013). These were accompanied by in-situ meteorological and sea ice observations from the meteorological station at the British Antarctic Survey research station at Rothera, 3 km distant (Fig. 1b). The focus of the paper is on the time variability of both diapycnal mixing and the vertical heat fluxes between the CDW and AASW layers, and the relationship between these quantities and wind- and internal-tide processes that have been conjectured to drive vertical mixing on the WAP shelf. The role of double diffusive mixing is also considered.

2. Data

2.1. Acoustic Doppler Current Profiler (ADCP) and Conductivity-Temperature-Depth (CTD) data

Horizontal velocities u and v were acquired every 15 min in 4 m vertical bins, from a moored 75 kHz Acoustic Doppler Current Profiler (ADCP) ensonifying the top 200 m of the water column at a position close to 67° 34′S, 68° 14′W for the period 25 January 2005 to 9 April 2007. This data set, known as the Rothera Time Series (RaTS) Site 1 (Fig. 1b), was fully described by Wallace et al. (2008). The instrument was deployed for three separate periods in 520 m of water, these being 25 January 2005 to 15 February 2006 (hereafter known as deployment 1), 17 February 2006 to 16 December 2006 (deployment 2) and 17 December 2006 to 9 April 2007 (deployment 3).

Accompanying these velocity data, full-depth (520 m) CTD data were acquired at approximately two-week intervals throughout the year, these measurements being taken either from a small rigid inflatable boat or through a hole drilled in the fast ice. Full details are given in Venables and Meredith (2014). After calibration, temperature T is accurate to 0.002 °C and salinity S to 0.005.

2.2. Estimating turbulent dissipation ε and diapycnal diffusivity κ

In the absence of direct microstructure estimates, turbulent kinetic energy dissipation ε was estimated using a finescale parameterization based on wave-wave interaction theory (Gregg et al., 2003). The alternative technique of estimating ε from Thorpe scales was considered, but the difficulty of estimating CTD package motion from the hand-winch CTD at Rothera rendered this technique inappropriate for this data set.

Estimates of buoyancy frequency squared (N^2) were calculated from the 1 m CTD time series, and then smoothed vertically using a 10-point median filter and interpolated onto the 15-minute time-base of the ADCP data. Vertical shear was then evaluated at each timestep, and spectra then produced of $\langle V_z/\overline{N}\rangle^2$ (hereafter known as buoyancy-normalized shear). This quantity was then averaged over one day to