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# Energetic plumes over the western Ross Sea continental slope

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[1] Rapid descent of dense Drygalski Trough (western Ross Sea, Antarctica) shelf water over the continental slope, within 100 to 250 m thick benthic plumes, is described. Speeds of up to 1.0 m/s are recorded flowing at an average angle of 35° to the isobaths, entraining ambient Lower Circumpolar Deep Water en route. This process is predominant in determining the concentration and placement of the shelf water injected into the deep sea as a precursor Antarctic Bottom Water. Nonetheless, a 4-hour duration pulse of undiluted shelf water was observed at depth (1407 m) directly north of the Drygalski Trough, moving at around 90 degrees to isobaths, and at a speed of 1.4 m/s. Thus the export of Ross Sea shelf water to the deep sea is accomplished within plumes descending at moderate angle to isobaths, punctuated by rapid downhill cascades. *INDEX TERMS:* 4500 Oceanography: Physical; 4207 Oceanography: General: Arctic and Antarctic oceanography; 4211 Oceanography: General: Benthic boundary layers; 4283 Oceanography: General: Water masses. **Citation:** Gordon, A. L., E. Zambianchi, A. Orsi, M. Visbeck, C. F. Giulivi, T. Whitworth III, and G. Spezie (2004), Energetic plumes over the western Ross Sea continental slope, *Geophys. Res. Lett.*, *31*, L21302, doi:10.1029/2004GL020785.

## 1. Introduction

[2] The ocean bottom potential temperature is colder than 1°C with the exception of the North Atlantic. The widespread colder water, Antarctic Bottom Water (AABW), is drawn from the continental margins of Antarctica, where dense shelf water descends as a gravity current or plume over the continental slope. Two of the mechanisms postulated by *Baines and Condie* [1998], also recently described by *Foldvik et al.* [2004] in the Weddell Sea, involve relatively undiluted flow channeled by local topography, and broad laminar flow which entrains less dense ambient water en route. Based on chlorofluorocarbon concentrations the escape rate of shelf water around Antarctica is estimated as 5.4 Sv (Sv = $10^6$ $m^3$/sec), which with entrainment of ambient water forms 8.1 Sv of AABW, exceeding the 7.6 Sv formation rate of >1°C lower North Atlantic Deep Water (NADW) [*Orsi et al.*, 2001, 2002].

[3] Export of dense Antarctic shelf water occurs in the Weddell Sea, Ross Sea, Adelie Coast and Prydz Bay, and probably other areas [*Baines and Condie*, 1998; *Whitworth et al.*, 1998; *Orsi et al.*, 1999; *Jacobs*, 2004]. The objective of this paper is to provide an initial report on the stratification and velocity characteristics of energetic descending gravity currents observed adjacent to Drygalski Trough over the continental slope of the Ross Sea, to alert the community of the nature of gravity currents over the slope of Antarctica.

[4] The western Ross Sea has been identified as a formation site for a particularly salty variety of AABW [*Jacobs et al.*, 1985; *Orsi et al.*, 1999] and model results suggest it is an important area of off-shelf transfer of water [*Dinniman et al.*, 2003]. From February through March 2003 as part of the AnSlope program, the research vessel *N.B. Palmer* carried out a survey (Figure 1) of the thermohaline and velocity fields of the western Ross Sea continental slope, with simultaneous measurements by a microstructure profiling system (CMiPS). The CMiPS data are being used to evaluate the benthic and interfacial stresses of the gravity currents described in this paper (Padman and others). In addition, moorings with current, temperature and salinity sensors were deployed on the outer shelf and slope to monitor shelf-slope fluxes for two years, with a small subset recovered for repositioning after three weeks. Although the first years' data from the full array are now available in preliminary form, the conclusions drawn from the short-term records concerning high frequency events are not significantly enhanced by the full data set. Preceding the *Palmer* survey were CTD observations from the *Italica* (CLIMA program) in January into February 2003.

[5] High sea ice concentration during the austral summer 2003, possibly associated with the presence of a nearly stationary 200 km by 40 km iceberg, C-19 to the south, centered near 74°S and 175°E, made the field operations challenging. In May 2003 C-19 drifted out of the Ross Sea close to Cape Adare. The benthic layer stratification over the slope, well below the iceberg draft of (estimated) 250 m, is unlikely to be affected by C-19.

## 2. Western Ross Sea Slope Plume Thermohaline Stratification

[6] The energetic nature of the continental slope benthic boundary layer is evident in the temperature, salinity and velocity profiles from three typical CTD/LADCP stations (Figure 2). The CTD data from these and other stations show an abrupt transition at 100 to 250 m off the sea floor, near a potential temperature (θ) of 0°C, from the more gentle θ and salinity (S) stratification of the lower circumpolar deep water (LCDW) into a much colder benthic layer. Salinity and $\sigma_1$ density anomaly differences across the transition are on average 0.05 and 0.2, respectively, accom-

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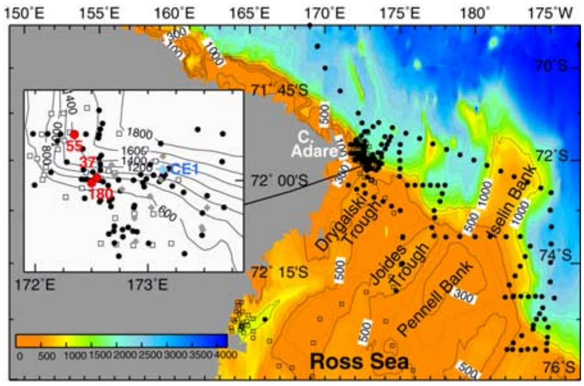

**Figure 1.** January–February 2003 *Italica* cruise CTD stations (black squares) and February–April 2003 *N.B. Palmer* cruise CTD/LACP stations (black circles). Also shown, the mooring locations (gray diamonds; CE-1 mooring: light blue diamond). The bathymetry contours are every 200 m; for the larger map the 300 and 500 m isobaths are added. The bathymetry was compiled from *Smith and Sandwell* [1997] north of 72°S and from an unpublished bathymetry map by F. J. Davey and V. M. Stagpoole (personal communication). The *N.B. Palmer* Multibeam data is at Antarctic Multibeam Bathymetric Synthesis URL: http://www.marine-geo.org/antarctic/.

panying a temperature drop of over 1°C. Often a homogeneous bottom layer, of an average thickness of 50 m, but occasionally as thick as 150 m is observed. Over the lower slope (>1500 m) the benthic layer is thicker with a weaker discontinuity from the overlying water.

[7] The general sense of the θ/S trend (Figure 2) of the slope benthic layer implies a freezing point end-member source of high salinity shelf water (34.76 to 34.80). Such water is found within the Drygalski Trough, the westernmost trough of the Ross Sea shelf [*Jacobs et al.*, 1985; *Bergamasco et al.*, 2002]. The Drygalski Trough attains depths greater than 1000 m and is filled with near freezing point water of greater than 34.8 salinity. The January–March 2003 data along the northern topographic sill of Drygalski Trough of about 500 m, reveal shelf water salinity of 34.80 to 34.83. The shelf high salinity water extends east of Drygalski Trough but is of lower salinity at the sill depths. For example, at the northern end of Joides Trough (immediately east of Drygalski; Figure 1) shelf water reaches only 34.76 (Figure 2). CTD data over the continental slope east of the Drygalski Trough do not detect water salty enough to account for the saline slope plume adjacent Drygalski Trough (Figure 3).

[8] Data from the central Ross Sea slope (176°W) show evidence of escape of lower salinity shelf water [*Jacobs et al.*, 1985; *Bergamasco et al.*, 2002]. The lower salinity plumes feed the northward bottom flow along the east flank of Iselin Bank, but do not appear to flow southward over the western flank of Iselin Bank (Figure 3), and may instead spread into the southeast Pacific Basin, as suggested by bottom water flow patterns [*Orsi et al.*, 1999]. However, the two homogeneous intervals within the station 180 benthic layer (Figure 2) indicate that lower salinity benthic layer water spreads westward over the slope adjacent to Drygalski Trough, but it is lifted about 100 to 150 m off the sea floor by the denser Drygalski water.

## 3. Western Ross Sea Slope Plume Velocity

[9] The LADCP data indicate the presence of swift bottom currents, often in excess of 1.0 m/s with 0.3 m/s in the overlying deep water. Removal of the barotropic flow, which is strongly tidal [*Padman et al.*, 2002], isolates the velocity associated with the benthic gravity current. This was accomplished by subtracting at each station the average velocity of the water column from 200 m depth down to 300 off the sea floor. With this done, the average bottom speed (lower 20 m) over the slope interval from 700 to 1500 m

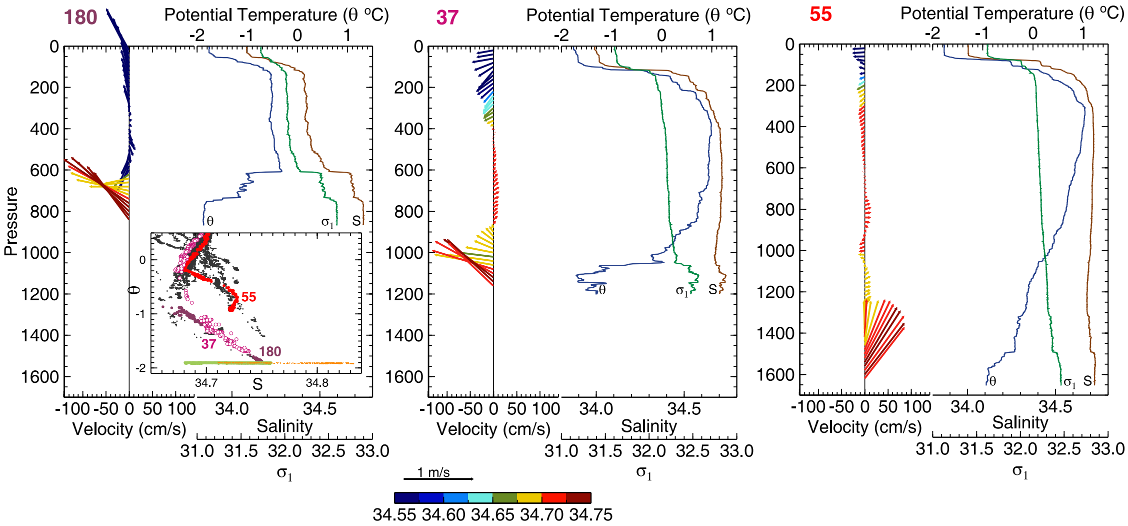

**Figure 2.** θ°C (blue), salinity (orange), σ-1 (density anomaly at 1000 decibars; green) vertical profiles at three CTD stations (Figure 1, red circles). Velocity profiles from LADCP are color coded for salinity. The inset shows the θ/S scatter of the three stations (red colors) with all stations west of 174°E within the 700 and 1500 m isobaths (black). Also shown are the Drygalski Trough high salinity shelf water (orange line) and the lower salinity type from the Joides Trough (green line).

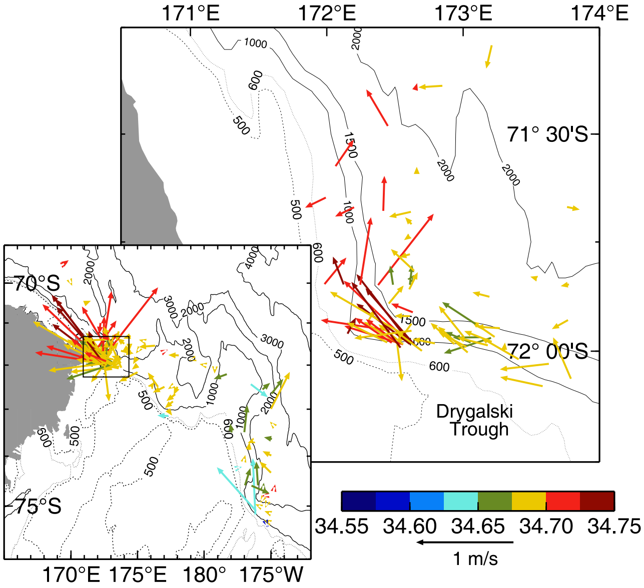

**Figure 3.** Bottom velocity (lower 20 m average) determined by the LADCP for stations deeper than 600 m. The vectors are color-coded for salinity. Isobaths every 1000 m plus the 600 m (dotted line) and 500 m (dashed) isobaths. The detailed area within the rectangle in the smaller map is shown enlarged in the background.

(Figures 2 and 3) of the survey region is 0.45 m/s. West of 174°E, marking the Drygalski Trough longitude, the characteristic bottom speed is 0.70 m/s, with a maximum of 0.9 m/s. The benthic layer speeds correlate with salinity, with the saltier bottom water associated with higher speeds. The internal Froude number is estimated from the velocity difference across the mid-point of the benthic layer cap, with the reduced gravity of the benthic water to fall within the range from 0.7 to 1.2, straddling the division between subcritical and supercritical flows implying significant entrainment with the ambient water.

[10] The bottom flow is predominantly directed towards the west with a rather large downslope angle relative to the regional isobaths, ranging from 10 to 47° with an average of 35°. The saltier (denser) plume water descends at the greater angle. The flow turns northward along the north-south trending isobaths off Cape Adare, with a lower angle of descent. The descent from the 700 m isobath from just inshore of station 180 to the 1600 m depth at station 55 is accomplished within 10.4 to 16.2 hours (using a range of plume speeds from 0.70 m/s typical of the Drygalski plume to the regional average speed of 0.45 m/s).

[11] The θ/S relationship of the slope stations of the western Ross Sea is used to determine the ratio of the cold shelf water to the warmer LCDW end-member. Initially, near 700 m the benthic water is about 60 to 80% shelf water, whereas at 1500 m it is closer to only 20 to 40% shelf water. The increase in benthic layer thickness from 100 to 250 m on descent from the upper slope to the mid-slope approximately matches the θ/S based estimate of shelf water dilution by LCDW, suggests an influx of LCDW rate or entrainment speed of 2 to 4 mm/sec. The 250 m thick benthic layer off Cape Adare flowing between the 700 and 1500 m isobaths with a mean speed of 0.45 to 0.70 m/s yields a transport of 1.7 to 2.6 Sv. The θ/S relationship of this water suggests that it is roughly a 30:70 admixture of shelf water (freezing point, 34.8) to LCDW (0°C, 34.69), indicating a 0.5 to 0.8 Sv export of western Ross Sea shelf water, about 9 to 15% of the circumpolar total of shelf water export determined by CFC data [*Orsi et al.*, 2001, 2002].

## 4. Sporadic Events

[12] Short term variability within the benthic layer is also detected at the mooring located directly north of the Drygalski Trough (Figures 1 and 4) at 71°57′S and 173°13′E (sea floor at 1407-m) deployed from 3 to 22 March. During most of the 19 day record θ°C and S vary in phase following the regional θ/S relationship of the deep water. However, 4 events of brief occurrences of colder, saltier bottom water (Figure 4) stand out. The largest, event #2, occurred on 12 March, lasting for about 4 hours. Although the extreme characteristics of these 4 events are quite dramatic, they represent only 2.9% of the record.

[13] During event #2 the bottom θ°C abruptly dropped to −1.66°C from approximately −0.3°C, accompanied by a salinity increase to 34.78 from 34.68. The bottom flow was directed towards the NW at over 1.4 m/s, in sharp contrast to the generally northeast-southwest trend of the 0.5 m/s tidal current oscillation (Figure 4). The peak θ/S excursion is coincident with the maximum velocity. At 1207 m there was only a weak θ/S indication of the 4 events, with no signal at the current meter at 1007 m; the four events are bottom intensified. All four events occur within an hour after the

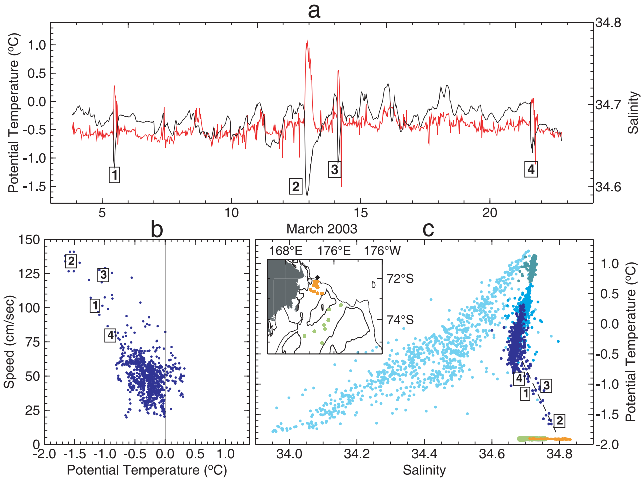

**Figure 4.** Mooring CE-1 (71°57′S; 173°13′E; sea floor 1407 m) time series, 3–22 March 2003. (a) The bottom salinity (red) and θ°C (black) recorded by a Microcat at 1397 m. Four cold/salty events are labeled. (b) The scatter of bottom θ°C vs. bottom current speed recorded by a RCM-8 Aanderaa at 1387 m. (c) The θ/S scatter at the 4 depths recorded at CE-1: 107, 707, 1207 and 1397 m. The four cold events fall along a straight mixing line (dashed line) between the lower CDW and the Drygalski Trough high salinity shelf water (orange line); the Joides Trough salinity (green line) is too fresh to serve as the source. The inset map shows the location of the *Italica* and *Palmer* stations used to define the Drygalski and Joides shelf water.

time of a strong tidal current, suggesting that the events may be coupled to the tides.

[14] The $\theta$/S scatter of the four events falls along a straight line connecting two end-members. The warmer end-member is at approximately −0.5°C, and the colder end-member falls within the Drygalski Trough shelf water (Figure 4). The warm end-member of −0.5°C is colder than that indicated by the CTD stations to the west, suggesting that during the outflow events the Drygalski shelf water is mixing with a relatively undisturbed deep water column. The coldest water of event #2 represents an 80% contribution of Drygalski freezing shelf water, more concentrated than typical of that depth within the Drygalski plume to the west. Because all four events show salinities higher than available from the Joides Trough (Figure 4) a descent at nearly right angles to the isobaths is required, far steeper than the descent angle derived from the CTD/LADCP stations described above. Speeds of 1.4 m/s would cover the distance from the 700 m isobath to CE-1 (8 km) in about 1 hour.

## 5. Discussion

[15] We present near synoptic observational evidence of entraining gravity currents descending within the lower 100 to 250 m of the water column over the western Ross Sea continental slope. Over the upper slope the benthic layer is composed of roughly 70% near freezing point, high salinity shelf water (−1.9°C; 34.8) drawn from the northern sill of Drygalski Trough. Over the mid-slope near 1500 m the benthic layer is warmer and less saline, due to entrainment of LCDW, with approximately a 30% shelf water component. The CTD/LADCP station array (Figure 1) does not allow for detailed tracking of the slope plume beyond Cape Adare, but the bottom water northeast and northwest of Cape Adare recorded by the AnSlope cruise, indicates that it is likely that the Drygalski Trough outflow continues to entrain as it spreads into the deeper ocean environment.

[16] After removing the barotropic (predominately tidal) current, the average bottom water speed over the upper to mid slope, as measured by the LADCP in bottom tracking mode, is 0.45 m/sec, with the most saline water associated with the highest bottom speeds (and greatest descent angle), approaching 1 m/s in the western Ross Sea. The water within the plume spreads westward, descending at an average angle to the isobaths of 35°, allowing transfer of dense shelf water from 700 to 1500 m in 10.4 to 16.2 hours.

[17] Episodes of more rapid downhill cascading of concentrated shelf water are evident from the near bottom (1407-m) current and $\theta$/S data obtained during a 19 day (3 to 22 March 2003) record from a mooring directly north of the Drygalski Trough. Four cold salty bottom water events each lasting for 3 to 4 hours were recorded. The water characteristics of the four events indicate that the source water is derived from the Drygalski Trough. During the strongest event on 12 March, the bottom temperature abruptly dropped to −1.66°C, accompanied by a salinity increase to 34.78 with northwest bottom flow of 1.4 m/s. Unlike the steady delivery of undiluted Shelf Water to the deep levels (>1600 m) of the continental slope just north of the Filchner Depression described by *Foldvik et al.* [2004], there is no apparent bottom ridge steering the pathway of outflow from the Drygalski Trough.

[18] In summary, we find that the export of Ross Sea shelf water onto the continental slope occurs within plumes descending at moderate angle to isobaths, punctuated by rapid downhill cascades to greater depths. The former is far more persistent and thus may be of greater significant to ocean ventilation. While full analysis of the AnSlope data will commence with the final mooring recovery in 2005, it is reasonable to surmise that the initial descent of a dense shelf water pulse would be at a steep angle to the isobaths, but as the Coriolis force takes hold, the veering angle approaches that of geostrophic balance, within the constraint of benthic layer friction. For larger outbreaks of dense shelf water greater depths may be reached during the pre-geostrophic phase.

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