Impacts of bottom corrugations on a dense Antarctic outflow: NW Ross Sea

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[1] Prominent seabed corrugations, axially oriented roughly down-slope, are present along the Antarctic continental slope. We use analytical and numerical model results to assess the potential impact of these corrugations on outflows of dense shelf water that contribute to Antarctic Bottom Water. Down-slope flow increases with increasing corrugation height and varies with along-slope wavelength. For parameters appropriate to the northwest Ross Sea, where heights and wavelengths are ~10–20 m and ~1.5 km, respectively, we estimate that the corrugations increase the down-slope transport of dense water, relative to the smooth bottom case, by ~13%. Corrugations enhance entrainment and reduce along-slope speed of the dense outflow. Larger amplitude corrugations (~100 m) observed in other regions may impact outflows elsewhere around the poorly mapped Antarctic continental margin. Our results emphasize the need to consider small-scale local topography when modeling dense outflows. Citation: Muench, R. D., A. K. Wåhlín, T. M. Özgökmen, R. Hallberg, and L. Padman (2009), Impacts of bottom corrugations on a dense Antarctic outflow: NW Ross Sea, Geophys. Res. Lett., 36, L23607, doi:10.1029/2009GL041347.

1. Introduction

[2] High resolution bathymetric surveys around Antarctica frequently identify “corrugations” over the continental shelf and upper slope that are axially oriented roughly down-slope [Davey and Jacobs, 2007; Noormets et al., 2009]. These features have typical trough-to-crest heights $H_C$ of 10–100 m and along-slope trough-to-crest wavelengths $\lambda_C$ of order 1 km (Figure 1).

[3] Dense shelf water, formed through surface cooling and brine rejection from sea ice growth and through sub-ice-shelf processes, exits over the shelf break and slope as dense outflows. These outflows contribute to the production of Antarctic Bottom Water (AABW), the dominant abyssal water mass in the world ocean [Johnson, 2008]. Here we explore the hypothesis, suggested by recent model results [Wåhlín, 2002, 2004a; Özgökmen and Fischer, 2008], that corrugations on the slope can enhance the down-slope transport of dense water. Our study is motivated by bathymetric and oceanographic data from the Antarctic Slope (“AnSlope”) experiment in the northwest Ross Sea [Gordon et al., 2004, 2009], but bears on dense outflows elsewhere around Antarctica including the Weddell Sea [Gordon, 1998; Foldvik et al., 2004] and the Adélie Land Coast [Rintoul, 1998].

2. NW Ross Sea Dense Outflow

[4] Dense high salinity shelf water (HSSW) formed on the continental shelf of the western Ross Sea flows northwards to the shelf break along several troughs. The HSSW feeds dense, bottom-trapped outflows that can be traced flowing westward along the continental slope [Gordon et al., 2009]. We focus here on the westernmost outflow, from the Drygalski Trough (Figure 1), which was extensively documented by the AnSlope field program. The pathway and volume transport of this outflow were estimated for summer 2003 using potential temperature $\theta$ and salinity $S$ as water mass tracers and detided currents derived from a lowered acoustic Doppler current profiler (LADCP) [Gordon et al., 2004, 2009]. Outflow current speed was $\sim 0.5$ m s$^{-1}$ and the associated volume transport was $\sim 1.7$ Sv, of which $\sim 0.4$ Sv was HSSW. The outflow varied in thickness from ~30 m near the shelf break during neap tides to more than 200 m farther down-slope during spring tides [Muench et al., 2009]. This variability reflects entrainment and a pronounced fortnightly variability in locally strong tidal currents [Muench et al., 2009].

[5] The NW Ross Sea area seafloor (Figure 1) was mapped using a vessel-mounted multibeam system [Davey and Jacobs, 2007]. Typical depth over the continental shelf is ~500 m. The continental slope under the Drygalski Trough outflow is steep; ~1:10 directly down-slope from its mouth, increasing to ~1:6 within ~10 km to the west. An extensive field of seafloor corrugations underlies the outflow over most of the slope (~500–2000 m depths). The most obvious corrugations trend down-slope and have typical along-slope wavelengths $\lambda_C$ of ~1.5 km and vertical trough-to-crest heights $H_C$ of ~10–20 m (Figure 1). Examination of their origins exceeds the scope of this paper. However, we speculate, in agreement with Davey and Jacobs [2007], that they may reflect current scour associated with jet-like down-slope flow events of dense water as reported by Gordon et al. [2004].

3. Analytical Model

[6] We consider the model geometry shown in Figure 2, following Wåhlín [2004a]. Figure 2 and the following discussion are for the southern hemisphere case. The down-slope and westward along-slope directions are $x$ and $y$, respectively. The seafloor has a constant slope $s_y$ downward in the $x$-direction, parallel to the corrugation axes. The corrugations consist of troughs and ridges extending from...
the shelf break to the deep sea, with along-slope wavelength \( \lambda_C \) and amplitude \( H_C/2 \) (Figure 1). Bottom elevation is \( h_C(x,y) = s_B x + \frac{H_C}{2} \cos \left( \frac{2\pi y}{\lambda_C} \right) \), dense layer thickness is \( h_0(y) \), and the interface \( \eta \) between the dense layer and ambient fluid approaches \( \eta = h_C + h_0 \) moving downslope.

A dense outflow is viewed here as a stationary, geostrophic along-slope bottom flow with a down-slope frictional component. In the presence of corrugations, down-slope transport converges in each trough, a portion then flowing down-slope within the trough rather than continuing along isobaths. The tendency for flow to parallel isobaths and exit the troughs [Nof, 1983; Wahlín, 2004b] is balanced by bottom drag within the troughs that generates an Ekman transport to the right of the flow direction and counters the tendency to parallel isobaths. If down-slope speed is sufficiently large, the two cross-corrugation flows will balance each other [Wahlín, 2002, 2004a]. In this case the main flow is down-slope along the trough, and secondary cross-corrugation flows are superimposed on this motion (Figure 2). The cross-corrugation flow component in the benthic boundary layer is the Ekman transport \( m_E(y) \) to the right of the down-slope flow, in the negative y-direction. Cross-corrugation flow above the boundary layer is \( v h_0(y) \), to the left of the down-slope flow (where \( v \) is cross-corrugation velocity in the y-direction). Steady down-slope flow can be maintained if \( m_E + v h_0 = 0 \), where \( v = \frac{g'}{u_G} \), \( m_E = \delta_E u_G \), \( g' \) is reduced gravity for a dense outflow underlying less dense ambient water, \( f \) is the Coriolis parameter, and \( u_G \) the geostrophic speed in the down-slope (x) direction. Ekman benthic layer thickness \( \delta_E \) can be estimated as \( \delta_E = C_D \frac{g'}{u_G} \) [Wahlín and Walin, 2001; Wahlín, 2004a]. Parameter values

**Figure 1.** (top left) Bathymetry in the northwest Ross Sea. Red box shows region of high resolution multibeam bathymetry data [Davey and Jacobs, 2007] shown in other plots. Blue circles show locations of CTD/LADCP profiles used to define the path of the dense water outflow from the Drygalski Trough sill northwestward along the continental slope. (top right) 3-D multibeam bathymetry for the region shown on the map, viewed from the NNE (red arrow on map): red shading indicates upper slope and shelf; dark blue is deep water. Black lines show 500, 1000 and 1500 isobaths. Red line near 1500 m shows location of depth transect across the corrugations. (middle) High-pass filtered bathymetry along the transect shown in Figure 1 (top right), with definitions of \( \lambda_C \) and \( H_C \). (bottom) Along-slope bathymetric trace from the Amundsen Sea upper slope [Noormets et al., 2009].
4. Numerical Simulations

Two numerical models were used as a qualitative check on the analytical results and to better visualize flow behavior down a corrugated slope. The impact of varying $\lambda_C$ on downslope flow was addressed using the nek5000 model [Fischer, 1997], which has been previously employed for dense outflow simulations [Özgökmen et al., 2004; Özgökmen and Fischer, 2008] and integrates the three-dimensional non-hydrostatic Boussinesq equations using the spectral element method. A second series of simulations investigated the impact of varying $H_C$ on downslope flow using the Generalized Ocean Layer Dynamics (GOLD) model, an isopycnal-coordinate, hydrostatic model. Use of these two different models allows us to identify robust (model-independent) features of the solutions and to better understand the limitations of different approaches. The typical for the Ross Sea ($C_D = 2.5 \times 10^{-3}$, $g' = 2 \times 10^{-3}$ m s$^{-2}$, $s_h = 0.1$ and $f = 1.3 \times 10^{-4}$ s$^{-1}$ [see Muench et al., 2009]) yield $\delta_E = 30$ m. The balance can also be expressed as

$$-\delta_E g' \frac{\partial}{\partial y} (h_C + h_0) + h_0(y) \frac{g's_b}{f} = 0,$$

where $u_C = \frac{\partial}{\partial y} (h_C + h_D)$. Equation (1) can be rewritten as

$$\frac{\partial u_C}{\partial y} - \frac{h_0(y)}{\lambda_C} = \frac{\partial u_C}{\partial y},$$

where

$$\beta = \frac{\lambda_C s_b}{\delta_E}.$$
The hydrostatic GOLD model reveals interactions between small-scale flows and larger scale features of the circulation (e.g., mesoscale irregularities, as noted in the text), and also can represent under-resolved dynamics of this nature in future OGCMs. In contrast, Nek5000 integrates Boussinesq equations and relies more on resolved than parameterized dynamics.

The nek5000 model simulated a physical domain with dimensions of 12 km, 6 km and 2 km in the down-slope, along-slope and vertical directions, respectively, and assumed a 2 km deformation radius for the outflow. A 0.4 m thick flow was introduced into the interior onto a bottom slope $s_b = 0.1$. The upper boundary condition was rigid lid and free slip. The model mesh consisted of 5,184 elements and 8th-order polynomials, yielding $2.7 \times 10^6$ spatial points with the mesh spacing $\delta = (\Delta x \Delta y \Delta z)^{1/3}$ varying within the range $9.8 \text{ m} \leq \delta \leq 34 \text{ m}$. Five simulations were carried out, including a smooth bottom case and two cases with $H_C \sim 200 \text{ m}$ and varying $\lambda_C$ (Figure 3). The outflow undergoes geostrophic adjustment until reaching a final state characterized by mesoscale fluctuations along the upper slope and a slow, downslope near-bottom Ekman flux. The corrugations markedly enhance down-slope flow relative to the smooth bottom case (Figure 3). This flow increased as $\lambda_C$ was decreased from 2 km to 700 m, passing through the “realistic” 1.5 km value for the Ross Sea and approaching 0.5 km where the analytical model predicts optimal down-slope transport. These results confirm an enhancement of down-slope flow by corrugations and an increase in transport with decreasing $\lambda_C$, consistent with the analytical results.

Figure 3. Three-dimensional view of the non-dimensional shelf water density perturbation from three nek5000 model simulations, each at the same time step, for: (a) smooth bottom, no corrugations, showing downslope Ekman drainage; (b) $H_C = 200 \text{ m}$ and $\lambda_C = 2 \text{ km}$, showing enhancement of downslope flow; and (c) $H_C = 200 \text{ m}$ and $\lambda_C = 700 \text{ m}$, showing still greater enhancement of downslope flow with decreasing $\lambda_C$. An animation of the complex evolution of the density perturbation field for case b is available from http://www.rsmas.miami.edu/personal/tamay/3D/corrugations-b.gif.

The GOLD model simulations were forced by a 0.15 Sv outflow of dense water introduced at the top of a slope with $s_b = 0.1$ (Figure 4). The outflow is 0.2 kg m$^{-3}$ denser than ambient water, consistent with Gordon et al. [2009] and with values used in the above analytical calculations. Inflow was geostrophically balanced, similar to the “DOME” configuration [Legg et al., 2006], and the 250 m horizontal resolution resolved the $\sim 2 \text{ km}$ outflow deformation radius. Shear-driven mixing was provided through the parameterization of Jackson et al. [2008]. Results from a subset of the simulations are illustrated in the horizontal plane.

Figure 4. Horizontal distribution of column-integrated tracer density for a tracer with initial concentration of 1 kg m$^{-3}$ introduced into the dense water outflow at the sill, using the GOLD model spun up for 4 days, for: (upper) smooth bottom case; (middle) case with $\lambda_C = 2 \text{ km}$ and $H_C = 20 \text{ m}$; and (lower) case for $\lambda_C = 2 \text{ km}$ and $h_C = 100 \text{ m}$. Impact of corrugations increases dramatically with increasing $h_C$. 4 of 6
using the column-integrated concentration of a tracer having an initial concentration in the dense outflow of 1 kg m⁻³ and zero in the ambient water (Figure 4). Isobaths on the figures emphasize the coincidence between the corrugations and downslope plumes. The smooth bottom results resemble those obtained using nek5000, with mesoscale instabilities on the upper slope. For \( H_C = 20 \) m, the effect on the outflow was evident but small. Increasing \( H_C \) to 100 m markedly enhanced downslope descent of the outflow and increased lateral spreading. This case resembles the \( H_C = 200 \) m, \( \lambda_C \sim 700 \) m run with the nek5000 model (Figure 3c). Tracer concentrations within the plume drop over shorter distances as \( H_C \) is increased, reflecting enhanced entrainment of ambient (tracer-free) water. Increasing \( \lambda_C \) in the GOLD runs (not shown) decreased the impacts, consistent with the analytical and nek5000 model results (Figures 2 and 3).

5. Discussion and Conclusions

[12] Seabed corrugations enhance the down-slope flow component and correspondingly decrease along-slope transport associated with a dense, bottom-trapped outflow. Down-slope flow increases with increasing corrugation height \( H_C \), and with decreasing wavelength \( \lambda_C \) down to an optimal value near \( \sim 0.5 \) km. These transport changes modify the location where dense outflow water is delivered to the deep ocean. Based on the tracer distributions in the GOLD model runs, corrugations enhance entrainment of ambient water into the outflow such that lower density outflow water is delivered to the bottom of the slope than for the smooth bottom case: this result is consistent with recent laboratory studies [Davies et al., 2006; Wåhlin et al., 2008; Darelius, 2008]. Enhanced down-slope flow due to corrugations might contribute to the anomalously large 35° down-slope flow angle reported for the NW Ross Sea dense outflow [Gordon et al., 2009].

[13] The nek5000 and GOLD model runs (Figures 3 and 4) both show generation of mesoscale instabilities in the outflow, whether or not corrugations are present. Recent numerical studies of Antarctic dense outflows [e.g., Padman et al., 2009] also show instabilities, and note the importance of flow variability due to “external” processes such as tides. These results suggest that the steady-state assumption of the analytical model (Figure 2) may not be appropriate to real dense outflows, and raise the possibility that the role of corrugations in setting mean outflow properties differs significantly from the idealized results reported here.

[14] Given the generally low quality of bathymetric mapping around most of the Antarctic continental margin, we cannot speculate on which density outflows might be influenced by corrugations. This study suggests, however, the length scales of features that are likely to impact outflows.

[15] Impacts described above might apply equally in the case of Ice Shelf Water (ISW) plumes that rise along the sloping bases of ice shelves after gaining buoyancy from addition of fresh water through basal melt [e.g., Holland and Jenkins, 1999]. Here, corrugations are associated with basal crevasses formed, for example, through tidal flexure at the ice shelf grounding line then migrating offshore with the mean ice shelf flow. While observations of crevasse dimensions are sparse, typical values for \( H_C \) and \( \lambda_C \) are \( \sim 10–100 \) m and \( \sim 1 \) km, respectively, suggesting that these may significantly impact buoyant plumes beneath the ice shelves.

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