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Downward flow of dense water leaning on a submarine ridge

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Abstract

Large-scale dense bottom currents are geostrophic to leading order, with the main flow direction along the continental slope. Bottom friction makes the water descend to greater depths, but only at a small angle to the horizontal. Here the effect of a submarine ridge that intersects the slope is considered. It is shown that the presence of a submarine ridge greatly enhances the downward transport. By leaning against the ridge it is possible for the dense water to flow downhill, perpendicular to the depth contours, even though the first-order dynamics are geostrophic. The requirement for downward flow next to the ridge is that the frictional transport that it induces is sufficiently large to counteract geostrophic advection along the isobaths and out of the ridge region. The dynamics are similar to those of downward flow in submarine canyons, but ridges appear to be more effective in channeling the dense water downhill, in particular for narrow ridges/canyons with small seaward slope of the ridge/canyon axis. The downward flow is analyzed using a simplified analytical model and the results are compared to data from the Filchner Overflow, which agree qualitatively with the model.

Keywords: Topographic steering; Dense plume; Density current; Ekman transport; Secondary circulation; Filchner Overflow; Antarctica; Weddell Sea

1. Introduction

The formation of dense water in marginal seas and over the continental shelves in high latitudes is an important part of the thermohaline circulation, and presumably of relevance for our climate. However important, the path that this dense water follows to the deep ocean and the dynamics governing it are not fully understood. A better understanding is needed to, for example, more correctly represent overflows in global-scale ocean models (Campin and Goosse, 1999; Legg et al., 2006).

Dense water entering an ocean basin through a gap or a strait will flow out along the continental slope as a plume of dense water. Such overflows are found for example in the Denmark Strait (Girton and Sanford, 2003), the Mediterranean Outflow (Ambar and Howe, 1979), the Faroe-Bank Channel (Mauritzen et al., 2005) and the Filchner Overflow (Foldvik et al., 2004). The dense water flows geostrophically along the isobaths, descending to greater depths only gradually because of friction (Killworth, 2001; MacCready, 1994; Wåhlin and Walin, 2001). Killworth (2001) predicted the descent

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rate of dense plumes on a smooth bottom slope to be 1:400, i.e. the plume water descends 1 m vertically while advancing 400 m horizontally. The downslope transport of dense water may, however, be increased by eddies (Chapman and Gawarkiewicz, 1995; Tanaka and Akitomo, 2001) or by topographic steering. The latter will be the focus of this paper.

The continental slopes of the ocean basins are in general not smooth but interrupted by canyons, ridges and topographic corrugations. Submarine canyons have been observed to steer dense water downslope, for example in the Wyville Thompson Ridge overflow, which descends inside a canyon intersecting the ridge (Sherwin and Turrell, 2005; Sherwin et al., 2007), and in the Adriatic Sea where a canyon steers a portion of the cold water down into the deep Jabuka Pit (Vilibic et al., 2004). Topographic steering, or channeling, of dense water in canyons has also been observed in models (Jiang and Garwood, 1998; Kämpf, 2000) and laboratory experiments (Baines and Condie, 1998; Kämpf, 2005).

The dynamics of a frictionally modified geostrophic flow down a canyon was analyzed by Wåhlin (2002). A purely geostrophic current can not have a net transport down along the canyon axis, since it is forced to translate parallel to the depth contours (Nof, 1983; Wåhlin, 2004), i.e., flow along the slope and out of the canyon region. In reality, bottom and interfacial friction will, however, always be present, inducing an Ekman transport to the left (right in the southern hemisphere) of the main current. With the aid of friction it is possible to sustain a steady downward flow inside the canyon, provided that the induced Ekman transport is sufficiently strong to balance the geostrophic slope advection out of the canyon. The dense water may thus remain in and flow down the canyon, while maintaining a transverse, secondary circulation much like the one observed within the canyon in the model study by Chapman and Gawarkiewicz (1995). A similar secondary circulation was also described and observed by Johnson and Ohlsen (1994) in their laboratory simulations of exchange flows through tubes and troughs.

Observations from the Filchner Overflow in the Weddell Sea, Antarctica, indicate that topographic steering also can take place in the vicinity of a submarine ridge (Foldvik et al., 2004). The Filchner Overflow consists of Ice Shelf Water (ISW), which is formed as water from the continental shelf in the southwestern Weddell Sea enters the cavity under the Filchner-Ronne Ice-Shelf and interacts with the glacial ice (Nicholls and Østerhus, 2004). ISW has a temperature below its surface freezing point (i.e. $T < -1.9\,^{\circ}C$), a salinity of 34.6 (Foldvik et al., 1985a), and the potential to sink to the bottom of the Weddell Sea and participate in the formation of Antarctic Bottom Water. It exits the ice shelf cavity through the Filchner Trough (Foldvik et al., 1985b) and then flows west along the continental slope. Data from a mooring placed in the vicinity of a submarine ridge crosscutting the continental slope west of the Filchner Trough show cold overflow water flowing downslope with great speed, and a nearby CTD section shows a layer of cold water leaning on the ridge. Downhill flow of dense water in the vicinity of a submarine ridge was also observed in the idealized model study by Jiang and Garwood (1998).

Here, downward channeling of dense water leaning on a submarine ridge is explored. It is shown that a dynamical regime similar to the one described for canyon-flow can be established also along a ridge. Analytical solutions are obtained for five idealized submarine ridge geometries, and expressions for their capacity to transport water downhill are derived. The obtained transport capacities are insensitive to the shape of the ridge and depend most strongly on the ridge height and width and the seaward slope of the ridge axis. The transport capacity is larger for gentle shelf slopes and steep ridge walls and for flows where the bottom boundary layer is thick compared to the ridge height. For such geometries, ridges are in fact more effective than canyons in channeling water downslope. The reason is that the downward ridge-flow then becomes rather wide and occupies a large area on the slope, while the canyon-flow is restricted laterally by the canyon walls. Data from the mooring and the CTD section mentioned earlier are compared to the theoretical results and are shown to agree qualitatively.

2. Theory

Fig. 1a shows a sketch of a (Northern-hemisphere) dense plume flowing over a topography with bottom elevation $D(x,y)$. The coordinate system is chosen so that the x-axis is pointing upslope. The thickness of the dense layer is $h(x,y)$ and it underlies an upper (lighter) layer that is infinitely deep and at rest. The two layers thus form a 1.5-layer system. Assuming that the Rossby numbers are small and