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# Seafloor Topography and Ocean Circulation

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## Introduction

Seafloor topography influences ocean circulation in two basic ways. First, it steers ocean flows. Second, it provides barriers that prevent deep waters from mixing, except within deep passageways that connect ocean basins or in hydraulically controlled overflow regions. This paper explores the impact of both of these processes on ocean circulation. The examples highlighted here were among the broad range of topics explored at a workshop on "Ocean Circulation, Bathymetry, and Climate," held at Scripps Institution of Oceanography in October 2002.

## Topographic Steering

Ocean currents cannot pass through ridges or seamounts. At ocean depths that are intersected by topography, currents steer around major topographic features. In addition, particularly at high latitudes, where the ocean is weakly stratified, geophysical flows tend to be vertically coherent (or barotropic) due to the Earth's rotation. As a result currents near the ocean surface align in roughly the same direction as deep ocean currents, and consequently often follow contours of constant depth, detouring around the bumps and troughs in the seafloor (e.g., Schulman, 1975). Most major currents respond to sea floor topography. The Antarctic Circumpolar Current (ACC), the Gulf Stream, and the Kuroshio Extension all steer around ridges and seamounts. Figure 1 shows estimates of the paths of the Subantarctic and Polar Fronts, the two major jets that comprise the ACC, superimposed over the seafloor topography of the Southern Ocean. The fronts flow to the south of the Campbell Plateau near New Zealand, and through the Eltanin and Udintsev Fracture Zones in the central Pacific Ocean. Just downstream of Drake Passage, around 60°W, they veer northward around the ridges of the Scotia Arc (Gordon et al., 1978; Gille, 1994).

To the extent that oceanographic flows are strictly barotropic, they should be steered along contours of constant $f/H$, where $f$ is the Coriolis parameter and $H$ represents ocean depth. Barotropic theory is often supported by observations. For example, floats in the Atlantic and Pacific Oceans preferentially spread along $f/H$ contours rather than across them, indicating that flow responds to topography (LaCasce, 2000).

In reality, because the ocean is stratified, and velocities tend to be faster near the ocean surface than at mid-depth, flow does not literally follow contours of $f/H$. Gille (2003) used float data to examine whether Southern Ocean velocities could be assumed to be equivalent barotropic, meaning that velocities attenuate with depth, with a fixed e-folding scale, $H_o$ (Killworth, 1992). Thus velocity $v(z) = v(0)\exp(-z/H_o)$. Under this assumption, flow is predicted to follow contours of $f/F_o$, where $F_o = H_o(1 - \exp(-H/H_o))$ (e.g. Marshall, 1995; Krupitsky et al., 1996). In the limit where the e-folding scale, $H_o$, is infinite, this is equivalent to assuming that flow follows $f/H$ contours. Since only large-scale topographic features of the sea floor are expected to steer large-scale circulation, topography was smoothed to eliminate variations with length scales less than 100 to 200 km. As illustrated in Figure 2, Gille (2003) found that in the Southern Ocean the equivalent barotropic model explains the largest fraction of variance in the flow data when an e-folding depth of about 700 m is assumed. This is consistent with other analyses of the Southern Ocean that have suggested that velocities decrease with e-folding scales between 500 and 1000 m, depending on position within the ACC and computation method (e.g., Karsten and Marshall, 2002).

Research using the Naval Research Laboratory (NRL) Layered Ocean Model (NLOM) has shown the influence of abyssal layer flow on the upper ocean in numerical simulations. Hurlburt and Metzger (1998) demonstrated how topographically steered mean abyssal currents can steer upper ocean currents as the Kuroshio Extension bifurcates in the vicinity of the Shatsky Rise (158°E, 33°N). Surface currents can bend

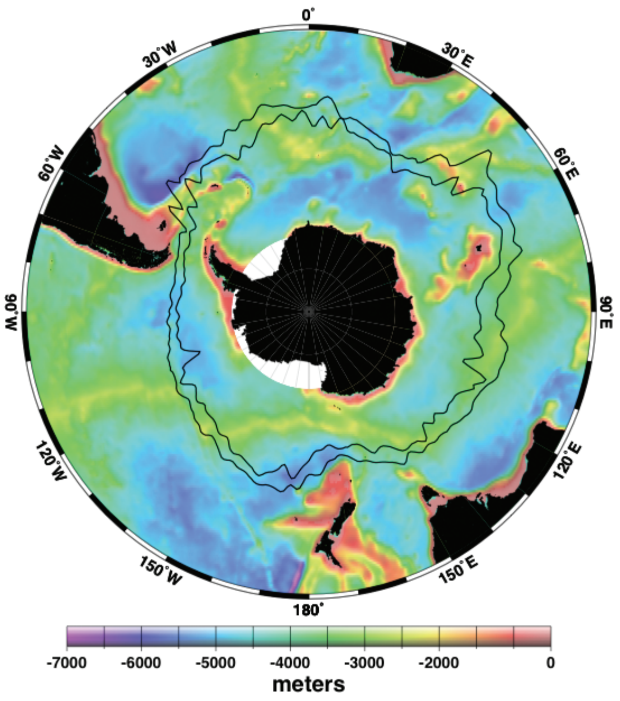

***Figure 1.*** *Paths of the Subantarctic (to the north) and Polar Fronts of the Antarctic Circumpolar Current, superimposed over Smith and Sandwell (1997) seafloor topography. Updated from Gille (1994).*

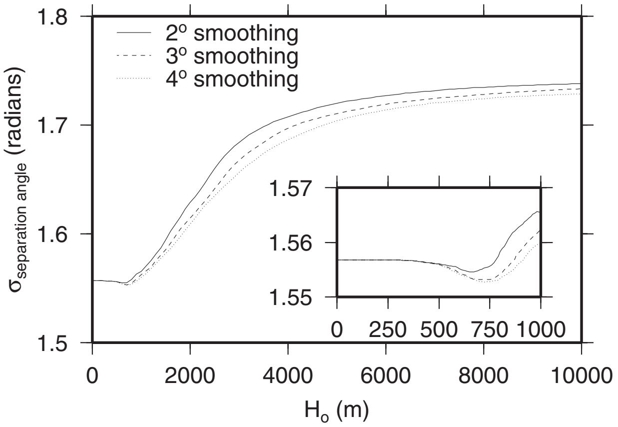

***Figure 2.*** *Standard deviation of angular separation between float velocities and direction of mean $f/F_o$ contours, as a function of e-folding scale $H_o$, where $F_o = H_o(1 - exp(-H/H_o))$. Solid, dashed, and dotted lines correspond to different degrees of filtering applied to topography. The inset enlarges the standard deviations for low $H_o$ to show the minimum around 700 m. From Gille (2003).*

in the direction of the abyssal currents. This is particularly noticeable for northward and southward meanders of zonal currents. Hurlburt and Thompson (1980, 1982) used the continuity equation in a two-layer model to show in a very clear and direct fashion how abyssal currents can steer upper ocean currents, especially where they intersect at large angles. In a multilayer case, the argument formally breaks down, but the steering effect remains in situations where the barotropic and first baroclinic modes are dominant, such as in western boundary currents or in the ACC, and the flow can be approximated by two layers (Hurlburt and Metzger, 1998).

Hogan and Hurlburt (2000) described an example of upper ocean-topographic coupling using 1/8° – 1/64° Japan/East Sea versions of NLOM. They noted that 1/32° horizontal resolution is required to produce baroclinically unstable surface currents. At that resolution, baroclinic instability is very efficient at transferring energy from the upper layers to the abyssal layer where the currents are constrained to follow the contours of the bottom topography. The result is a profound change in abyssal circulation compared to the coarser resolution simulations. In particular, the eddy-driven deep mean flows are much stronger and occur over most of the basin. A southward abyssal flow along the coast of Korea and an anticyclonic abyssal circulation around a ridge near 39°N, 130°E contribute to the separation of the East Korean Warm Current (EKWC) near 37° – 38°N as a result of the upper ocean-topographic coupling described above. These results demonstrate that the bottom topography in this region is critical for the EKWC to separate from the coast at these latitudes. An experiment that removed the ridge near 39°N, 130°E eliminated the offshore abyssal steering and consequently changed the separation latitude of the EKWC as shown in Figure 3.

The mean pathways of major current systems can also be significantly affected by accurate topographic information. Metzger and Hurlburt (2001) studied this in the vicinity of Luzon Strait, which connects the Pacific Ocean and the South China Sea (SCS). As the North Equatorial Current bifurcates along the east coast of the Philippines, the northward branch forms the beginning of the Kuroshio. Upon entering Luzon Strait, the Kuroshio intrudes westward into the SCS before retroflecting and continuing its poleward journey along the east coast of Taiwan. Using a 1/16° Pacific Ocean version of NLOM, the authors found that the westward extent of Kuroshio intrusion is highly dependent upon the accuracy of the coastline geometry of the island chain within Luzon Strait. Two small-scale shoals were found to have a significant blocking effect on the Kuroshio. Inclusion of the shoals had two effects on NLOM. First, they narrowed Luzon Strait and thus reduced the westward bending (a result consistent with Li et al. (1996)). Second, more importantly, they deflected the inflow angle making it more northward, thus reducing the westward intrusion as shown in Figure 4.

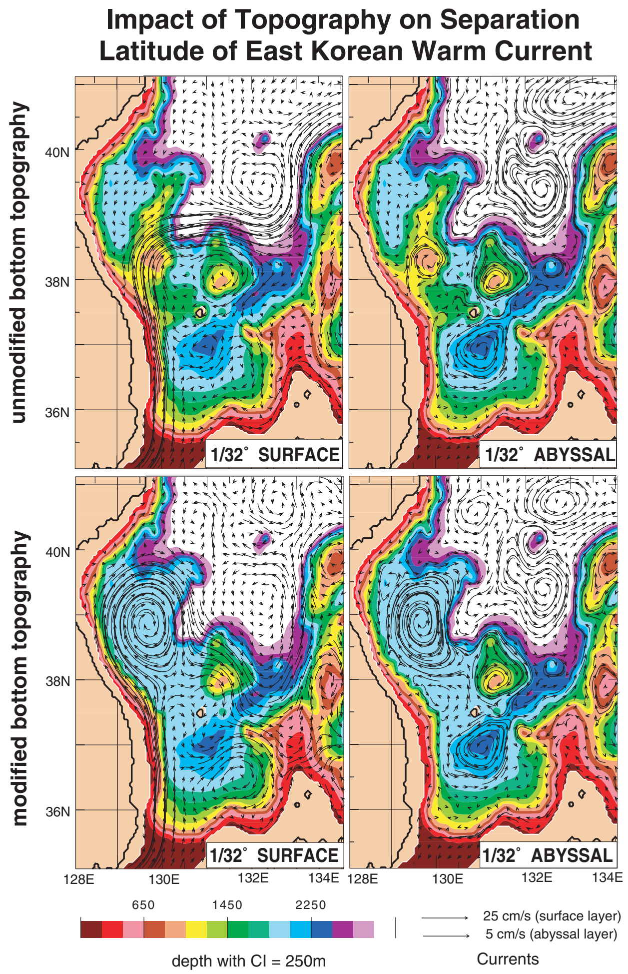

***Figure 3.*** *Bottom topography (color) and mean currents from 1/32° simulations of the Japan/East Sea using the NRL Layered Ocean Model in the region where the East Korea Warm Current (EKWC) separates from the coast. Only the southern portion of the model domain is shown. Left panels show surface currents and the right panels show abyssal currents. In the bottom row, the topographic ridge near 39°N, 130°E has been removed. This modified the offshore abyssal flow in this region and affected the separation latitude (37° – 38°N) of the EKWC. Adapted from Hogan and Hurlburt (2000).*

The NLOM simulation with the more accurate coastline geometry agrees more closely with the observational evidence of Qu (2000) and Liang et al. (2003).

Given the importance of very small-scale features in determining the pathways of major ocean currents, accurate representation of sea floor topography is crucial when doing high horizontal resolution ocean modeling. Unfortunately, most of today's topographic databases do not adequately resolve small-scale features. In the case of the island chain within Luzon Strait, significant hand editing using navigational charts from the Defense Mapping Agency was required to obtain realistic coastlines. Thus, higher resolution global bathymetry is needed.

## Flow Through Ridges and Gaps

Topography matters not only because it steers ocean flows, but also because it inhibits or enhances the mixing and transport of waters from different regions. Constrictions, such as narrow fracture zones or shallow sills, can play an important role in determining how water passes between different parts of the global ocean. For a review of the subject and theory see Whitehead (1998), which also contains a list of important passages and straits around the globe. Examples given here, from several ocean basins, illustrate the importance of such bathymetric features.

### *Nordic Seas and Atlantic Ocean Interface*

The overflow waters that flow from the Nordic Seas through the Denmark Strait and down the slope into the Atlantic basin contribute to the formation of North Atlantic Deep Water (Dickson and Brown, 1994). Colder, fresher water forms over the shelf and spills over the Denmark Strait, entraining warmer and more saline Irminger Sea water along the way. Historically, ocean models have had problems with dense water overflows that are crucial for accurate simulation of deep water properties and the overall global circulation budget. Part of the reason for this misrepresentation is that in these older models, the flow is determined mainly by the mixing and not by hydraulic or topographical processes (Käse and Oschlies, 2000).

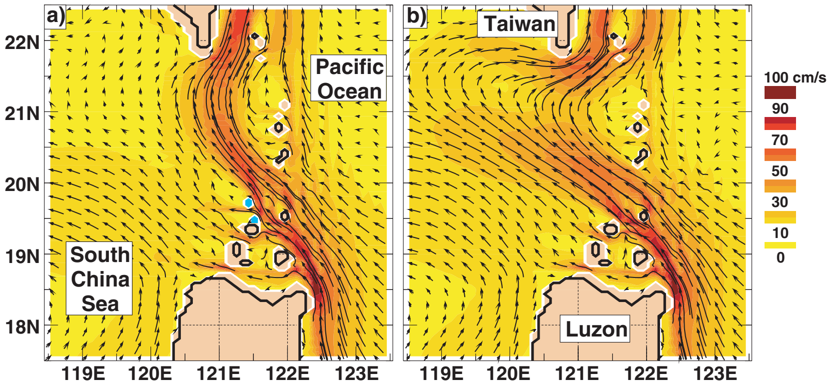

***Figure 4.*** *The 6-year mean upper layer speed and currents from 1/16° Pacific NLOM simulations (zoom-in on the Luzon Strait that connects the Pacific Ocean and the South China Sea) that **(a)** include Calayan Bank and the shoal north of Calayan Island and **(b)** exclude these three model gridpoints. The specified model gridpoints are highlighted in blue on the left panel. Adapted from Metzger and Hurlburt (2001).*

Recently, some realistic process-oriented numerical studies of the Denmark Strait (e.g., Käse and Oschlies, 2000; Shi et al., 2001) examined the nature of the flow in this region. Both papers included examples that used bottom-following coordinate systems and realistic bathymetry at a high resolution (4-7 km horizontally). The Denmark Strait is considered a wide sill, many Rossby radii (19 km at this latitude) in width, and it is v-shaped. Shi et al. (2001) found that when using realistic topography, the downstream characteristics of the flow were little changed with the inclusion of detailed bathymetry. They found that a change in the mixing scheme had a more profound effect on the downstream flow and its characteristics. Käse and Oschlies (2000), on the other hand, concentrated on examining the flow before it enters the strait and the effect of the topography on flow. Their conclusion was that the transport of the dense water through the strait is controlled by topography and modulated by the downstream eddy field. The volume transport is limited by the topography, as Killworth and McDonald (1993) theorized. They further found that while the heat transport fluctuations are largely due to the change in temperature upstream of the sill, the volume transport remains relatively constant. Thus, it is important to determine correctly sill depths and their extent in order to reproduce such flows properly in models.

> *Topography matters not only because it steers ocean flows, but also because it inhibits or enhances the mixing and transport of waters from different regions.*

Figure 5 shows, as an example from a primitive equation model, simulated February temperature and salinity sections at 31°W within the Denmark Straits overflow region. These sections are from a 1/12° (3-4 km at the latitude of Denmark Strait) HYbrid Coordinate Ocean Model (HYCOM), which uses a hybrid of isopycnal coordinates, terrain-following (sigma) coordinates, and fixed (z-level) vertical coordinate systems (see http://hycom.rsmas.miami.edu for details.) The hybrid vertical coordinate approach effectively handles such overflow situations (as a natural consequence of the model design). The depth of the sill is one of the controlling factors governing the details of the overflow, and it is necessary to know the bathymetry as accurately as possible.

Large-scale flows can also be extremely sensitive to the sill representation even in coarse resolution climate models. Roberts and Wood (1997) showed that in a coarse resolution ocean model, the heat transport northward past Iceland differs by a factor of two depending whether their model includes deep passageways through the sill that separates the Greenland-Iceland-Norwegian Sea from the North Atlantic, as illustrated in Figure 6. The coarse resolution used by Roberts and Wood (1997) does not fully resolve the sill features or the narrow hydraulic flow over the sill, but the strong sensitivity to topography indicates that climate change signals estimated from coarse resolution models may depend critically on the representation of seafloor topography in the models.

### *Mid-Atlantic Ridge*

In the tropical Atlantic Ocean near 22°S, 3000 m deep waters to the west of the Mid-Atlantic Ridge are high in oxygen, indicating that they have had relatively recent contact with the atmosphere and as a result may carry signatures of recent climate fluctuations. In contrast, waters to the east of the Ridge are low in oxygen (Mercier et al., 2000). The Mid-Atlantic Ridge, with a typical depth of 2500 m, separates these waters along most of its length. However, Figure 7 shows one location on the eastern flank of the Ridge where high oxygen water has managed to percolate through the ridge. This is a clear indicator that a fracture zone exists in the ridge. No deep fracture zone can be identified in existing Smith and Sandwell (1997) seafloor topography, but a detailed multi-beam survey identified a 3900-m deep sill that could explain the observed oxygen values. Because flow through the ridge is constrained to a narrow region and is hydraulically controlled, mixing within this gap may be strongly elevated compared with mixing elsewhere in the deep ocean. Deep sills, such as this one, are important for our understanding of the ocean's role in climate, because they help determine how deep waters can mix and ultimately how heat is transported through the ocean.

### *Indonesian Seas*

The importance of including the correct bathymetry in an ocean model is also seen in the data presented by Gordon et al. (2003). They discussed the bathymetric barriers within the Indonesian seas that influence the through flow of waters from the Pacific to the Indian Ocean, an important climatic choke point in the circulation of our global ocean waters. While most of the transfer of water is in the upper portion of the thermocline layer, Gordon et al. (2003) determined that there is a significant contribution from the deep layers. Some passages are as narrow as 30 km wide and 3250 m deep, such as Ombai Strait. This strait, they estimated, allows for the passage of 0.6 to 0.8°-$10^6$ $m^3$ $s^{-1}$ of deep water (below 680 m) or 10 to 20% of the total 4 to 6°-$10^6$ $m^3$ $s^{-1}$. The bathymetry used by the current generation of ocean models requires much hand editing and relies on ship surveyed depth measurements to define the important passages. While the *in situ* measurements made by this group have been extensive, they commented that most sills in the Indonesian seas have not been surveyed. The paper also suggests that the thickness of the overflow layer is determined by the sill topography itself (e.g., u-shaped or v-shaped) and that

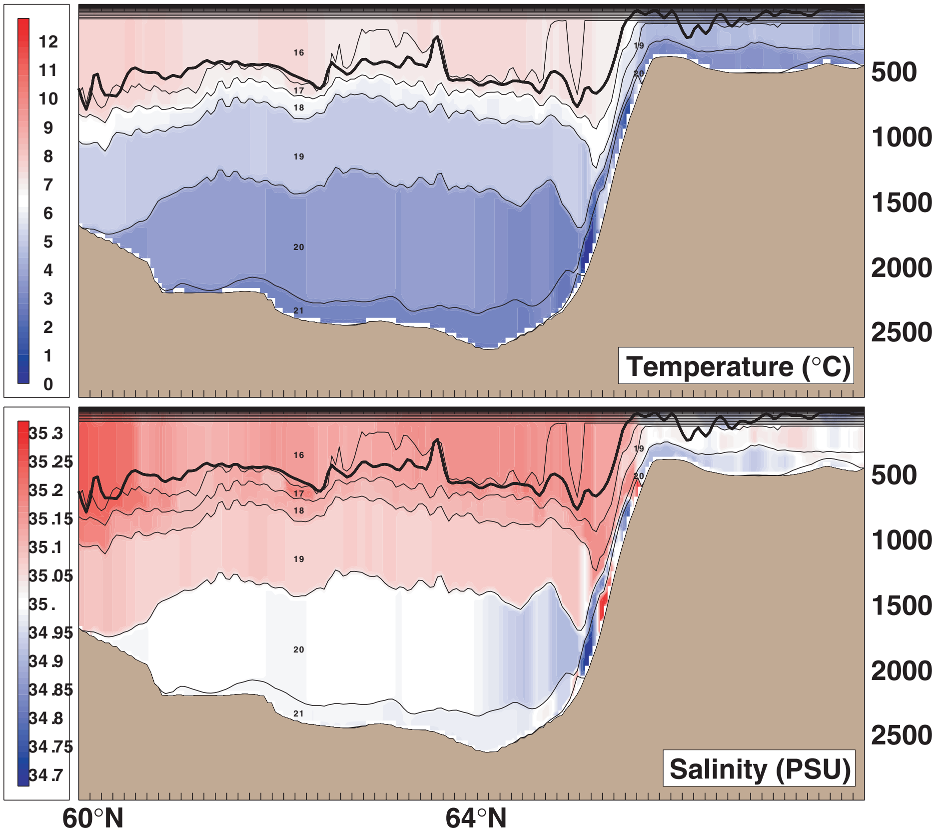

***Figure 5. (Top panel)*** *Temperature (°C) section for Denmark Straits overflow at 31°W in February.* ***(Bottom panel)*** *Salinity (PSU) section for same time and location. Both sections are derived from the 1/12° Atlantic HYbrid Coordinate Ocean Model (HYCOM), which uses a hybrid isopycnal/terrain-following (sigma)/fixed (z-level) vertical coordinate system. The thin black lines are the vertical coordinates and the thick black line is the mixed layer depth.*

these details influence the amount of water transported over or blocked in the region of the sill. With the resolution of models increasing, these types of details will need to be included in the bathymetry that the models incorporate into their domains.

### *Summary*

Both accurate bathymetric data and sufficient horizontal model resolution are required to simulate these overflows. Details of the passages and sills need to be known to a fine scale because of the use of high resolution models to study processes on regional scales, but also because the larger, climate models are becoming capable of running with higher resolutions. The detailed quantification of the bottom boundary of these models, such as the use of full, partial, or "shaved" cells as described by Griffies et al. (2000), will require a detailed and accurate bathymetry.

## Discussion: Requirements for the Future

In the future, ocean modelers are likely to become more acutely aware of the sensitivity of their models to topographic details. The highest resolution global ocean models that are currently in use have grid points roughly every 10 km. These models are barely able to respond to the smallest topographic features currently resolved, which have length scales of 20 to 30 km. Projections for the future (Figure 8) suggest that as computer power increases, model grid spacings will decrease to 5 km or less by 2010, and will respond to topographic features that are 10 km or less in length and are likely to require topographic position accuracies of ±2.5 km.

As horizontal resolutions are refined, vertical resolution also increases, as illustrated in the inset in Figure 8. Currently the largest deep ocean vertical separations are about 250 m. By 2010, average deep ocean vertical separations will decrease to 75 m or less, and models will therefore be sensitive to errors in bottom depth of 40 m or less.

These upcoming requirements for bathymetry with higher horizontal resolution and small vertical errors will pose a challenge to those who gather and archive bathymetric data. Coupled ocean/atmosphere

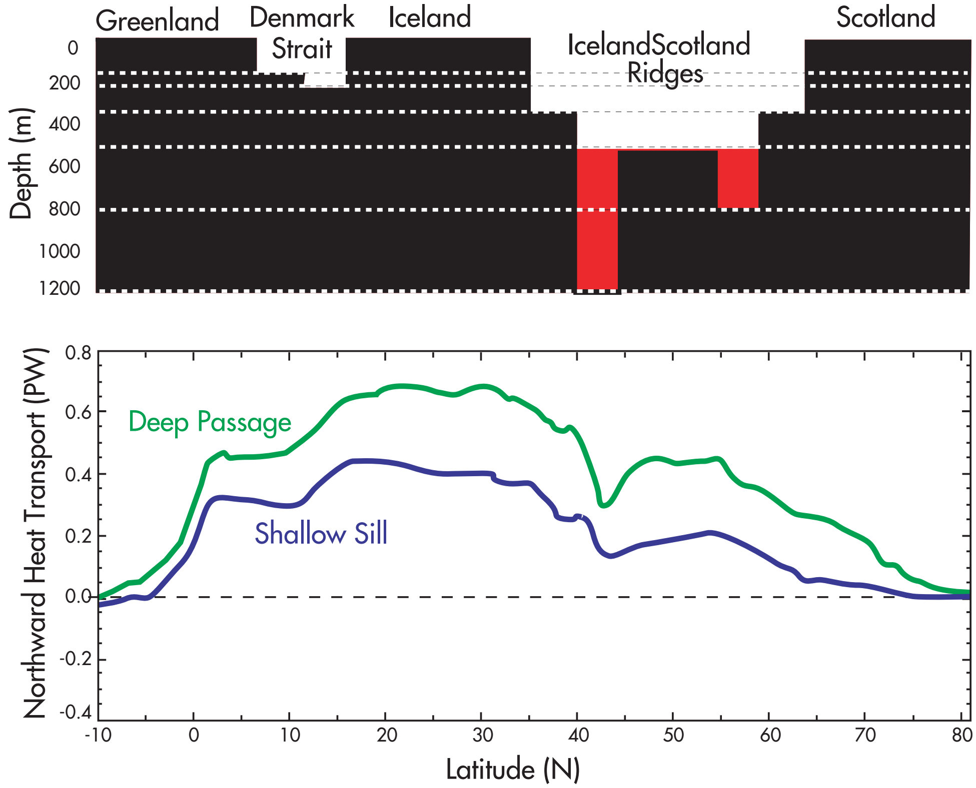

***Figure 6. (Top panel)*** *Profile of sill separating North Atlantic from Greenland-Iceland-Norwegian Sea for two scenarios of the coarse resolution climate model run by Roberts and Wood (1997). In the deep sill version areas shaded red are open; in the shallow sill version, red areas are closed.* ***(Bottom panel)*** *Poleward heat transport as a function of latitude for the two different sill configurations. Adapted from Roberts and Wood (1997).*

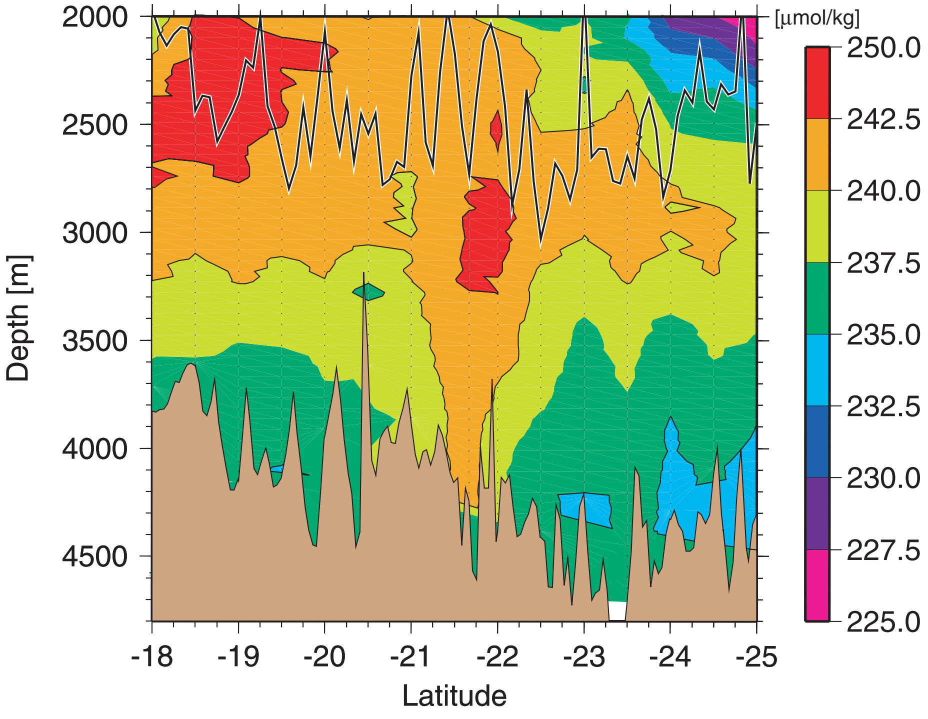

***Figure 7.*** *Oxygen concentration at 9°W in the Eastern South Atlantic. The mid-depth maximum (in red) indicates water that has found its way through the mid-Atlantic ridge into the eastern basin. For comparison, the solid black line indicates the peak height of the mid-Atlantic Ridge as reported in bathymetric databases. Figure adapted from Mercier et al. (2000) by Andreas Thurnherr.*

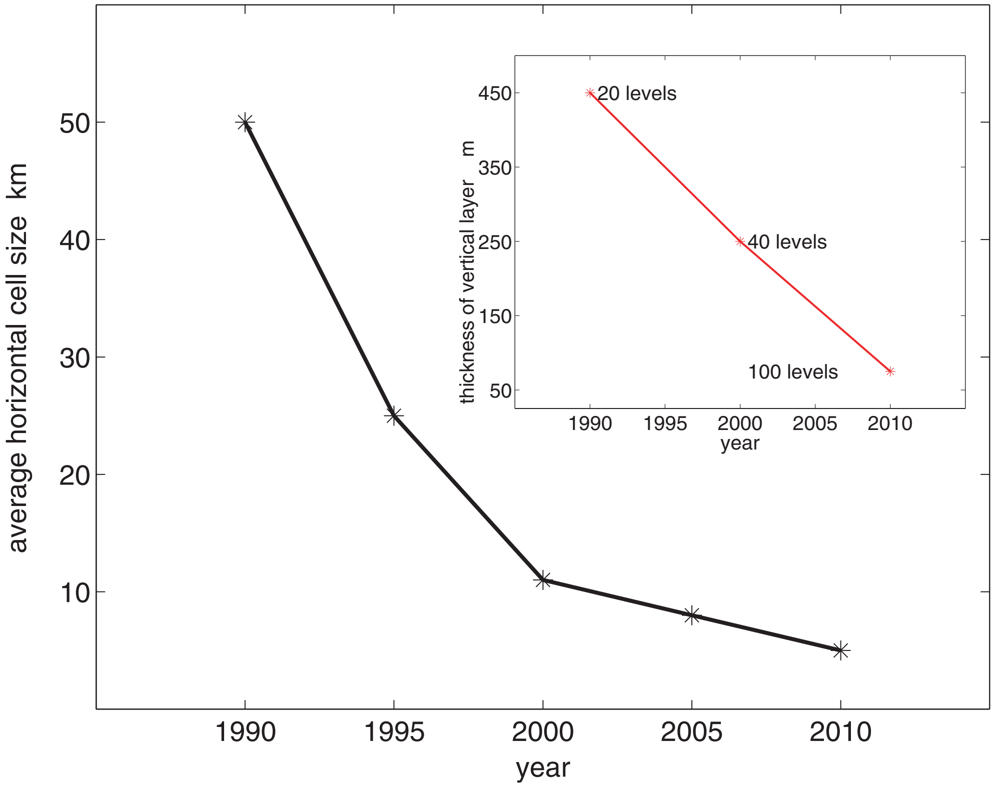

***Figure 8.*** *Trends in the resolution of global ocean circulation models. Resolution has become finer during the past decade, with production simulations routinely being run at resolutions of tens of kilometers horizontally and with the largest vertical separation between levels at 250 meters. Projections of the growth in computer power in the next 10 years suggest that by 2010 routine production runs of global ocean models will have horizontal resolutions averaging 5 km. Prepared by Robin Tokmakian based on current trends in computer modeling.*

models and models representing long-term climate change are likely to run at coarser resolution, but they will nonetheless require accurate bathymetry as well as good parameterizations of bathymetrically-controlled processes, such as hydraulic overflows, that occur at length scales smaller than model resolution.

## Summary

This paper has reviewed examples of two processes by which seafloor topography can influence ocean circulation. Topography can steer large-scale flow and it can contain water within basins so that adjacent water masses can mix only under specific conditions. Because topography blocks deep flow, and because ocean currents tend to be vertically coherent, topography can determine the path of even surface intensified flows. In addition topography strongly influences where deep water can pass between basins. This in turn determines how rapidly heat can flow through the deep ocean. Numerical models of ocean circulation are sensitive to the details of seafloor topography. Although at present bathymetry does not hinder the performance of most ocean circulation models, as model resolutions are refined and other problems are resolved in the next few years, bathymetry is likely to manifest itself as a critical requirement for climate and circulation studies. In anticipation of these future bathymetry requirements, oceanographers need to begin working with marine geologists and geophysicists now to ensure that the appropriate bathymetric data are collected and archived.

## Acknowledgments

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