BATHYMETRY AND OCEAN CIRCULATION

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Executive Summary

Bathymetry influences ocean circulation in several ways. First, it steers large-scale ocean circulation: even relatively small ridges on the sea floor can influence the direction of major ocean currents. In the deep ocean, ridges serve as solid barriers separating bottom waters in adjacent ocean basins. Gaps in bathymetry associated with fracture zones play an important role in determining how much water can pass between ocean basins and where these processes can occur.

Second, small-scale bathymetric features also influence ocean circulation. When ocean currents pass over rough sea floor, energy is converted from horizontal flow into vertically propagating waves. This can result in elevated levels of vertical mixing over rough sea floor topography.

Finally, ocean circulation and climate models are sensitive to the accuracy and resolution of the large-scale bathymetry that they resolve and to the mixing parameterizations for processes that they do not resolve. In the next ten years, model resolutions are expected to increase, and the importance of having accurate high-wavenumber bathymetry is expected to become increasingly acute.

1. Introduction

Bathymetry matters for ocean circulation. Large-scale bathymetry steers large-scale currents and separates water masses in neighboring deep ocean basins. Smaller-scale bathymetry, or bottom roughness, is linked to elevated levels of vertical mixing, and thus appears to be a major factor determining spatial variability in vertical mixing in the ocean. Together these two effects of bathymetry, steering and mixing, are important factors influencing global ocean circulation.

This paper reviews recent research exploring the influence that bathymetry has on ocean circulation and explores the impact that better bathymetry might have in refining our understanding of ocean circulation. Section 2 examines steering, which is normally associated with large-scale topographic features. Section 3 reviews the impact of bathymetry on small-scale mixing. Section 4 summarizes the combined impact of these processes on ocean circulation and climate models. The findings are summarized in Section 5.

2. Topographic Steering

Ocean currents cannot pass through ridges or seamounts, and hence deep currents are steered around major bathymetric features. In addition, particularly at high latitudes where surface and deep waters have similar densities, geophysical flows tend to be vertically coherent (or barotropic) due to the Earth's rotation. As a result currents near the ocean surface tend to align in roughly the same direction as deep ocean currents, and consequently tend to follow contours of constant depth, steering around the bumps and troughs in the seafloor. Figure 1 shows ocean current speeds inferred from floats deployed in the North Atlantic Ocean. These are superimposed over bathymetry, and indicate that strong flows nearly trace out contours of constant depth along the edge of the ocean basin.

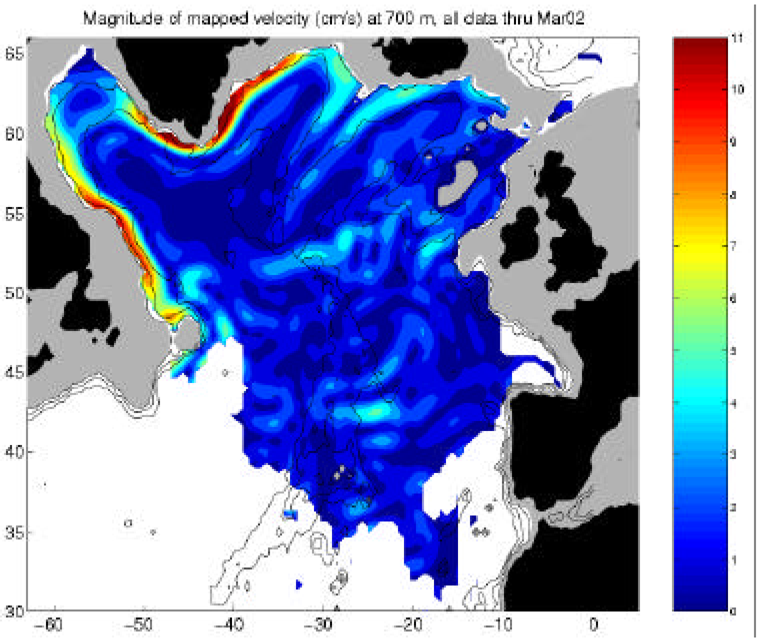

Figure 1: Ocean current speeds at 700 m depth, inferred from float velocities. Graphic provided by K. L. Lavender. See Lavender et al. [2002] for details.

Most major currents respond to bathymetry. The Antarctic Circumpolar Current (ACC), the Gulf Stream, and the Kuroshio Extension all steer around ridges and sea mounts. Figure 2 shows the paths of the Subantarctic and Polar Fronts, the two major jets that comprise the ACC, superimposed over the bathymetry of the Southern Ocean. The fronts steer 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. More detailed analysis by Gille [2003] indicates that the Southern Ocean flow is not precisely barotropic, but that its response to bathymetric is consistent with an "equivalent barotropic" model of the flow.

Topography matters not only because it steers ocean flows, but also because it prevents mixing of waters from different regions. While only the largest features of the ocean bathymetry seem to control bathymetric steering, narrow fracture zones can play an important role in determining where water passes between different parts of the global ocean. For example, in the tropical Atlantic Ocean near 9^{o}N, 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. The Mid-Atlantic Ridge, with a typical depth of 2500 m, separates these waters along most of its length. However, Figure 3 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] bathymetry, but a detailed multi-beam survey identified a 3900-m deep sill that could explain the observed oxygen values. 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.

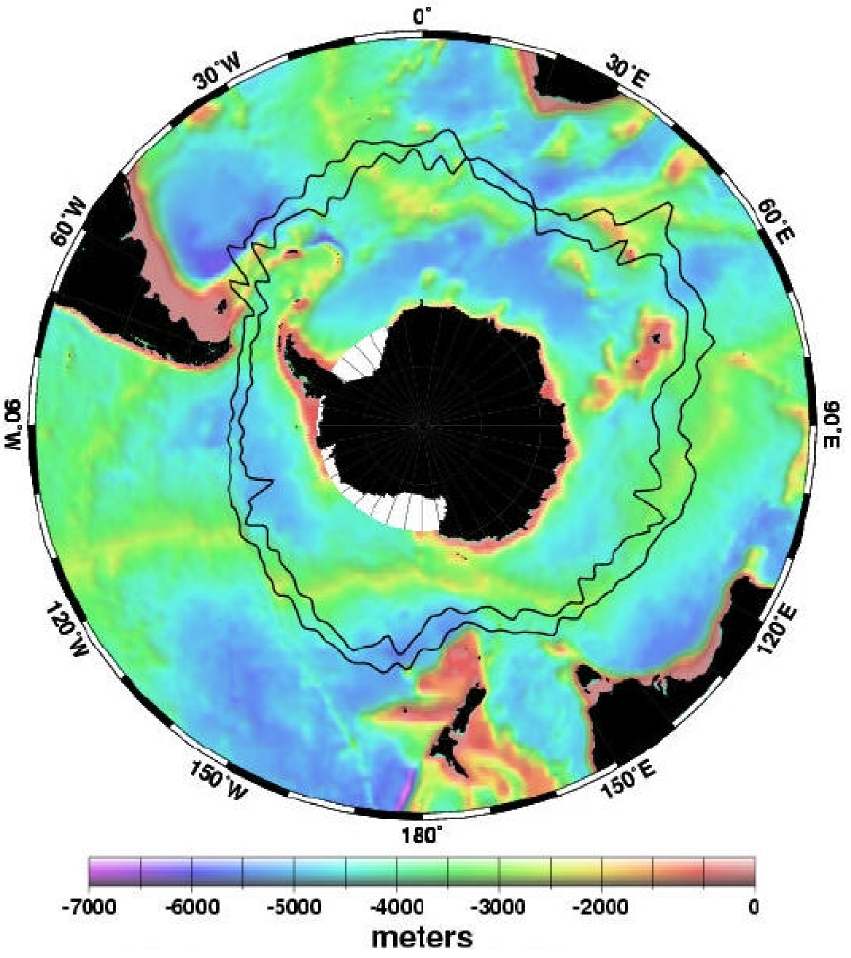

Figure 2: Paths of the Subantarctic and Polar Fronts of the Antarctic Circumpolar Current, superimposed over Smith and Sandwell [1997] bathymetry.

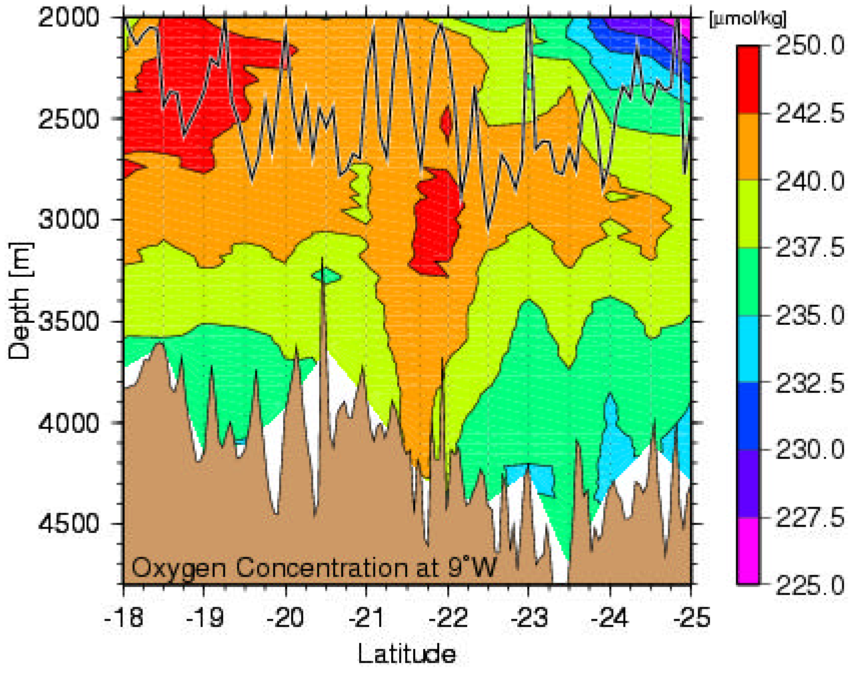

Figure 3: Oxygen concentration at 9 degrees West in the Eastern South Atlantic. The mid-depth maximum (in red) indicates water that has found its way through the mid-Atlantic ridge into the eastern basin. For comparison, the solid black line indicates the peak height of the mid-Atlantic Ridge. Figure adapted from Mercier et al. [2000] by Andreas Thurnherr.

1. Roughness and Mixing

Bathymetry matters to ocean circulation not only because its large-scale features block the passage of water, but also because its small-scale features influence the rate at which the ocean mixes. Mixing blends together waters with differing properties and therefore redistributes heat and tracers through the ocean. Small-scale bathymetry influences mixing in two ways. One way is represented by Figure 3. When water speeds through a narrow fracture zone towards the eastern side of the Mid-Atlantic Ridge, it gains a hydraulic pressure head. As a result, it rapidly mixes with the surrounding water in the outflow.

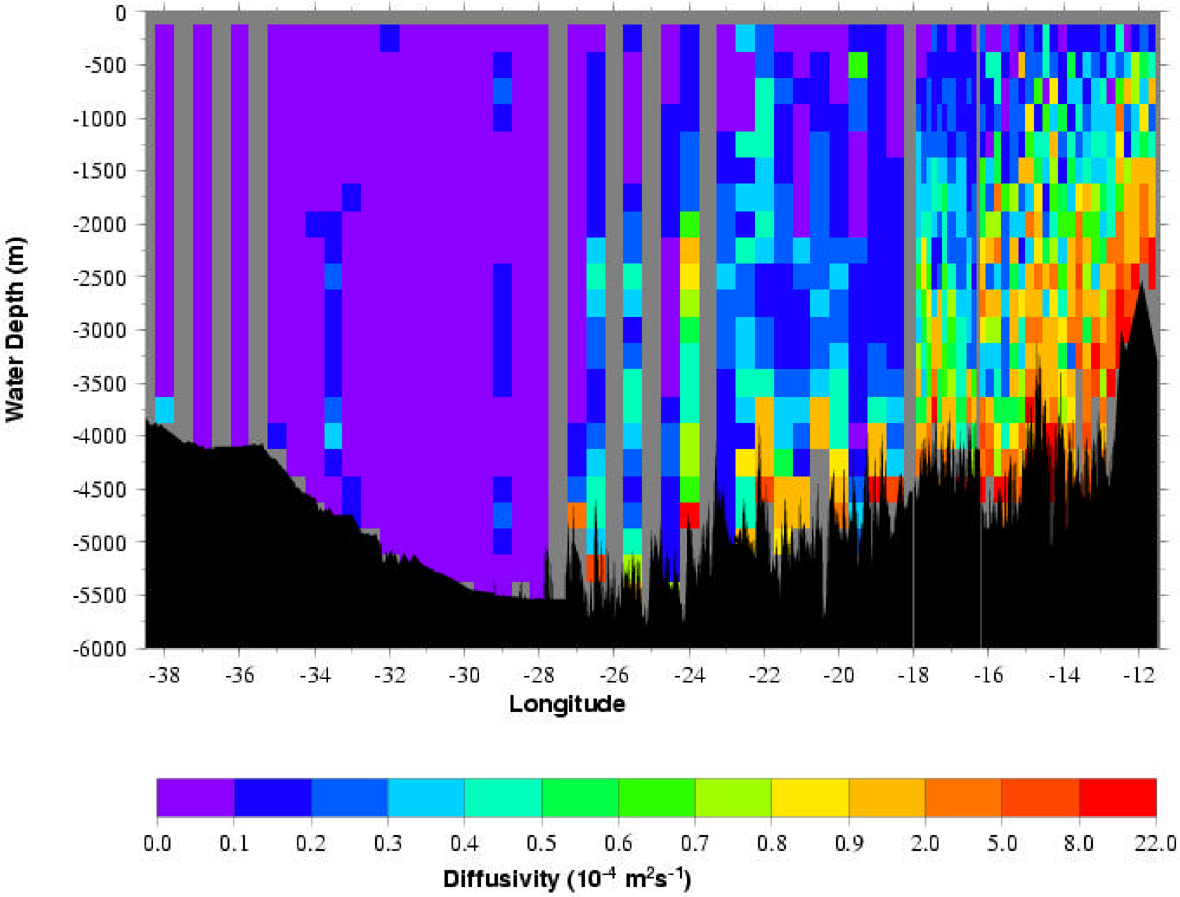

Figure 4: Depth-longitude section of vertical diffusivity inferred from velocity microstructure observations, from Mauritzen et al. [2002], based on observations reported by Polzin et al. [1997], with additional data from a later cruise [Ledwell et al., 2000]. Mixing is low over the smooth topography to the west and high over the rough topography to the east.

The second way that small-scale bathymetry can influence ocean mixing rates is determined by seafloor roughness. Figure 4 shows vertical diffusivities in the Brazil Basin, the eastern South Atlantic Ocean. West of 28°W the seafloor is smooth and vertical diffusivity is low. East of 28°W, the basin has rough bottom topography and vertical diffusivity is high, in places two orders of magnitude greater than in the west. As tides move water back and forth across the rough bathymetry, the energy associated with horizontal motions is converted into vertically propagating internal waves. These waves carry energy upward through the water column [St. Laurent and Garrett, 2002; Llewellyn Smith and Young, 2002] and result in increased vertical mixing. Mixing such as this is one of the factors controlling ocean stratification. Further field studies in the Pacific and Atlantic basins continue to analyze the role that bathymetry plays in ocean mixing. These measurements have confirmed the idea that vertical diffusivity is neither horizontally nor vertically uniform, as many ocean circulation and climate models once assumed. Future climate predictions will depend on developing accurate assessments of the spatial variations in vertical diffusivity.

The large-scale features of ocean bottom roughness [Figure 5] indicate that high roughness regions exist along the entire length of the Mid-Atlantic Ridge, and along parts of the Southern Ocean ridge structures. The Pacific Ocean is smoother, with more isolated sea mounts and no large regions of corrugated abyssal floor. In principle global maps such as the one in Figure 5 can be used to estimate the spatial variability of vertical diffusivity in the ocean. The details of this problem remain challenging. Theoretical studies suggest that accurate prediction of roughness-induced mixing would require that bathymetric features with wavelengths as small as 1 km be resolved. However, existing bathymetric datasets are unable to resolve features smaller than 20-30 km. If bathymetric data were able to resolve wavelengths as small as about 10 km, then existing empirical models of bathymetric spectra could be used to estimate higher wavenumber bathymetry. This would allow improvements in the estimates of vertical diffusivity.

Despite the limitations of current bathymetry, the global roughness data are clearly linked to oceanic dissipation rates. Egbert and Ray's [2000,2001] estimates from TOPEX altimeter data (not shown) indicate that tidal dissipation is concentrated near major rough bathymetric features, along the Mid-Atlantic Ridge and around the major island arcs of the Pacific Ocean. In contrast the comparatively smooth East Pacific Rise has little influence on tidal dissipation.

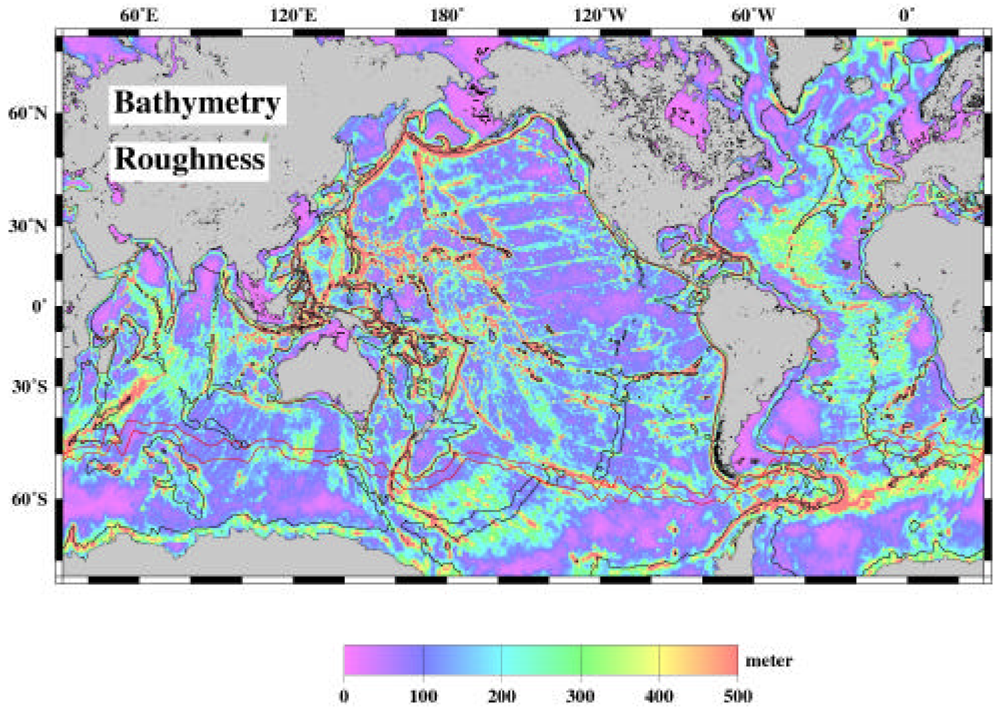

Figure 5: Global bottom roughness from Gille et al. [2000]. For this map, roughness was computed by smoothing squared topography over 160 km length-scales.

Tides provide most of the energy that can be converted from horizontal motions into vertically propagating waves, but they are not the only source of horizontal energy. Gille et al. [2000] correlated mesoscale eddy kinetic energy measured from satellite altimetry with bottom roughness. Their results (Figure 6) show that in the deep ocean, high roughness correlated with low eddy kinetic energy, implying that bottom roughness might be removing eddy kinetic energy from the system. The trend does not hold in mid-depth regions of the ocean, where there is no statistically significant correlation or in shallow areas where rough bottom topography can occupy a substantial fraction of the water column and appears to generate eddy kinetic energy.

These results indicate that predictions of ocean mixing rates depend on knowing the details of the bottom topography as well as understanding how ocean currents interact with the bottom.

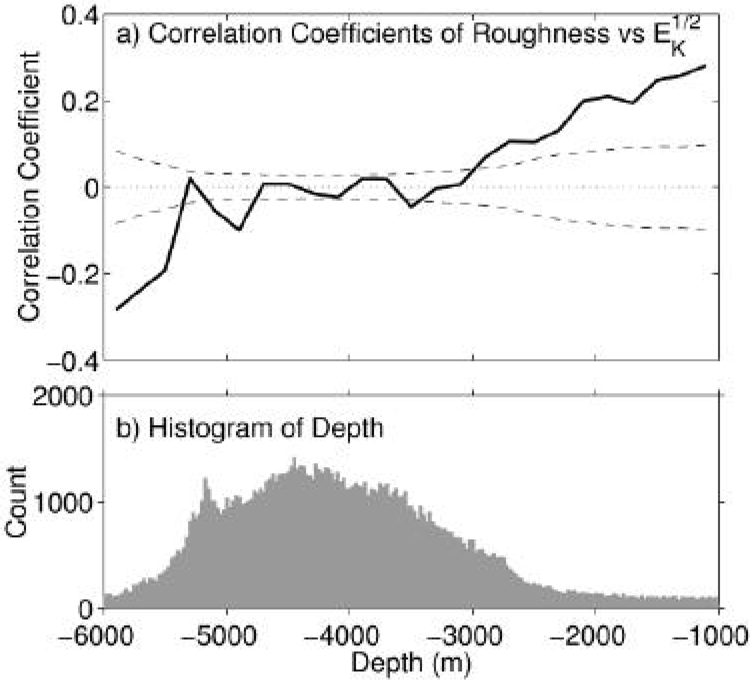

Figure 6: (a) Correlation coefficient of bottom roughness versus the square root of eddy kinetic energy ($E_K^{1/2}$) for data binned as a function of depth (solid line). The 95% confidence limits (dashed lines) indicate the range of correlation coefficients that are statistically indistinguishable from zero. (b) Histogram of ocean depths with some energy and latitude limits as above, sorted in 25 m bins.

4. Bathymetry's Impact on Model Predictions of Climate and Ocean Circulation

The ocean's response to bathymetry and roughness influences large-scale ocean circulation and heat storage in the ocean. For ocean circulation models, subtle details in ocean bathymetry can make the difference between erroneous and accurate simulations of the large-scale circulation. Figure 7 shows results from two different runs of the high-resolution 1/16 degree Naval Research Laboratory (NRL) Layered Ocean Model [Metzger and Hurlburt, 2001]. In the simulation on the left, three small islands or shoals in the Luzon Strait region just north of the Phillipines are correctly included, as indicated in blue. In this case, the modeled Kuroshio flows northward in agreement with observations. In the panel on the right, the bathymetric features are removed, and the Kuroshio intrudes unnaturally through the Luzon Strait into the East China Sea. Slight differences in bathymetry can hence completely modify the large-scale flow.

This sensitivity to bathymetry occurs in many other types of models as well. Roberts and Wood [1997] showed that in a coarse resolution ocean model designed for climate studies, the heat transport northward past Iceland differs by a factor of two depending whether their model includes deep passageways through the sill that connects the Greenland-Iceland-Norwegian Sea to the North Atlantic.

Climate models are also sensitive to the assumed rate of vertical mixing. Sokolov et al. [1998] showed that varying the vertical diffusivity in the ocean component of their coupled climate model influences the rate at which heat and greenhouse gases penetrate into the deep ocean. This in turn determines greenhouse gas concentrations in the atmosphere, which are lower when the ocean diffusivity is high. High diffusivity also allows heat to penetrate more quickly into the ocean and results in more rapid sea level rise. Their results suggest that accurate climate models depend on reliable assessments of vertical diffusivity.

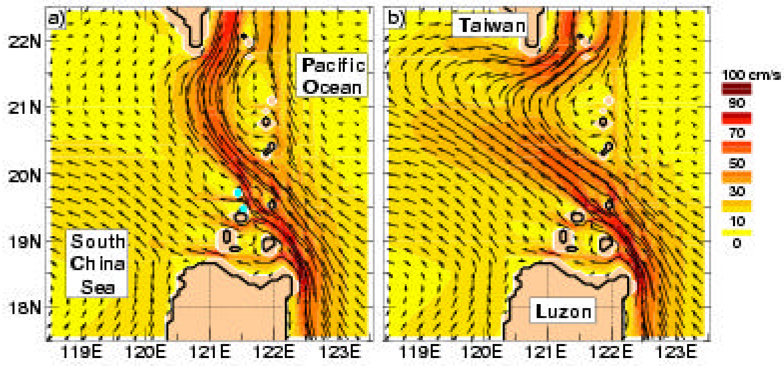

Figure 7: A 6-year mean of upper layer speed in the Luzon Strait (just north of the Phillipines) from two versions of the 1/16 degree NRL Layered Ocean Model (NLOM). Bathymetry included in the left panel steers the Kuroshio properly northward. Its omission in the right results in an unnatural intrusion [Metzger and Hurlburt, 2001].

In the future, ocean modelers are likely to become more acutely aware of the sensitivity of their models to bathymetric 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 bathymetric features currently resolved, which have lengthscales 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 bathymetric features that are 10 km or less in length. As horizontal resolutions are refined, vertical layer thickness also decrease, as illustrated in the inset in Figure 8. By 2010, average 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 and small vertical errors will pose a challenge to those who gather and archive bathymetric data.

5.Summary and Conclusions

Bathymetry influences ocean circulation both by steering large-scale flow and by influencing dissipation rates. This paper has reviewed examples of both types of processes. Because bathymetry blocks flow, it determines where ocean currents can go and where deep water can pass between basins. This in turn influences how rapidly heat can flow through the deep ocean. Rough topography also induces high vertical diffusivity, accelerating the vertical mixing of the ocean. This determines the stratification of the ocean and influences the penetration of heat and gases from the atmosphere into the deep ocean.

Numerical models of ocean circulation are sensitive to the details of bathymetry. 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.

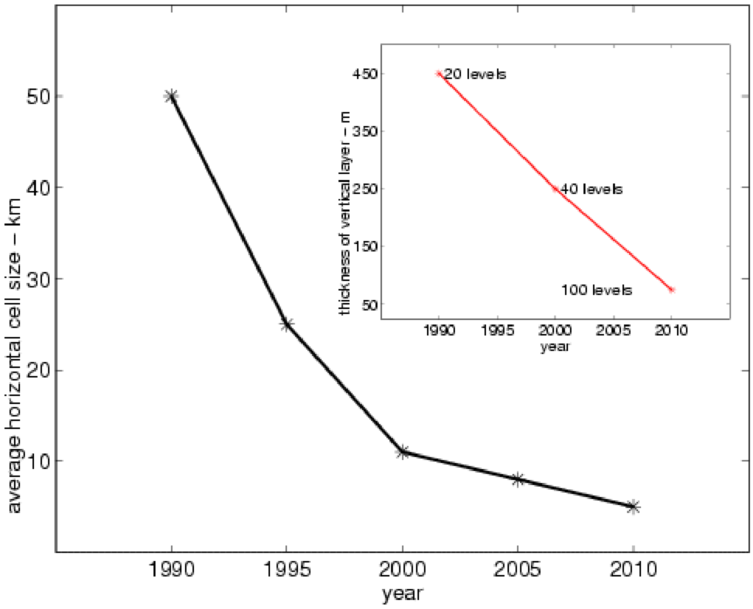

Figure 8: Trends in the resolution of global ocean circulation models. Resolution has become finer during the past decade, with production simulations routinely being run at resolutions of tens of kilometers horizontally and with the largest vertical separation between levels at 250 meters. Projections 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.

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