Topographic Effects in the Ocean

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The effects of seafloor topography on ocean circulations are more complicated and more influential than previously supposed. Recent advances, driven by intensive observational efforts and by increasingly powerful numerical simulations, show the crucial role that topography plays in abyssal circulations, mixing, ocean-shelf exchanges, and the rectification of time-dependent flows. Progress on these and related topics was reviewed at the eighth 'Aha Huliko'a Hawaiian Winter Workshop which was held January 17-20, 1995, at the University of Hawaii in Honolulu and drew together observers, numerical and laboratory modelers, and theorists.

Abyssal Circulations

Topographic influences are most felt by the deep abyssal circulations. Continental margins and ridges confine the flow to basins connected by narrow channels. These abyssal circulations are currently being mapped by ambitious observational programs; among them are the Synoptic Ocean Prediction (SYNOP) program in the Gulf Stream region between Cape Hatteras and the Grand Banks and the Deep Basin Experiment in the Brazil Basin. Both regions show complex flow structures governed by basin topography with in- and outflow through passages (N. Hogg). Flow through these passages might be critically controlled, as seen in laboratory experiments. A comparison of estimates assuming critical control with volume fluxes through the Romanche Fracture Zone, the Vema Channel, the Discovery Gap, and other passages (based on CTD data) shows general good agreement (J. Whitehead).

Numerical simulations of deep abyssal circulations employ various types of models. The flow of dense water from the southern Adriatic Sea into the eastern Mediterranean Basin was simulated by D. Haidvogel using an inverted 1½ layer reduced gravity model with prescribed inflow and uniform upwelling. R. Salmon employed a model based on an abridgement of the planetary geostrophic equations and applied it to the deep flow approaching the Samoan Passage. Numerical models often have to assume unrealistically large friction coefficients; R. Ford solved the linear wind-driven planetary geostrophic equations in realistic bathymetry with a triangular finite element net based on points that lie on a set of geostrophic contours and obtained solutions at much smaller values of friction than have previously been obtained. The aggregate force that topography exerts on mean flows is called "form stress" or "topographic stress". In a barotropic quasigeostrophic model, slightly elongated ridges with axes inclined to a uniform incident flow lead, surprisingly, to different stress regimes when the inclination angle is reversed (G. Carnevale).

Seamounts

An especially intensive observational program was conducted at Fieberling Guyot in the eastern North Pacific to study the flow at and around an isolated seamount. The observations show an anticyclonic vortex cap on top of the seamount produced by tidal rectification, internal wave spectra with peaks at the critical reflection frequency, and trapped diurnal (K1) oscillations that must be interpreted as vertically propagating vortex-trapped or evanescent waves rather than as strictly standing seamount-trapped waves (C. Eriksen, E. Kunze). The wave fields around the seamount are associated with regions of low Richardson numbers, density inversions, and enhanced turbulent mixing. Topographically trapped waves are also observed in other places, e.g., riding along portions of ridges and along rectilinear valleys, and exhibit energy levels well above "background" (D. Luther).

Critically reflected internal waves and topographically trapped waves are an energy source for enhanced turbulent mixing at seamounts and other topographic features. An open problem is how this "boundary mixing" affects the stratification in the ocean interior and whether or not it can account for the large effective diffusivities of several 10^{-4} m^2 s^{-1}, required by mass and heat balances in abyssal basins, and bigger than those found by direct microstructure turbulence measurements in the upper ocean. The observations at Fieberling Guyot suggest that internal waves do not provide enough energy for such a large effective diffusivity, but Fieberling Guyot may not be representative. Another open question is whether or not secondary flows can efficiently move mixed water away from the boundary or can restratify the mixed water.

The large data base obtained at Fieberling Guyot provides essential bounds for numerical simulation. Using a sigma-coordinate model, A. Beckmann investigated the strength and spatial structure of the rectified flow at the flanks and on the top of a steep isolated seamount. While many aspects of the simulation agree well with the observations at Fieberling Guyot, there are also discrepancies, especially in the time-dependent flow.

The phenomena of wave trapping at topography is of principal interest to theorists and often investigated with methods borrowed from theoretical physics. The circumstances under which trapping occurs at an isolated seamount are fairly well explored. M. Hendershott considered the extension to a random array of seamounts and identified circumstances for which geostrophic flow perturbations remain localized or propagate through the seamount array. The wave equation for long monochromatic surface gravity waves can be transformed to a Schrödinger equation, which facilitates the analysis of the possible wave modes. Trapping of a different kind occurs when a monochromatic internal gravity wave is introduced into a channel. Upon successive reflections the wave becomes focussed to a limiting trajectory (L. Maas).

Ocean-Shelf Exchanges

The coastal ocean meets the deep ocean at the continental shelf edge. The constraint that steep bathymetry poses on ocean-shelf exchanges can be broken by a number of processes: internal tides and waves; upwelling, fronts, and filaments; downwelling and cascading; along-slope currents, instability, and meanders; eddies; tides, surges, and coastally trapped waves. A preliminary assessment of this daunting list was made by J. Huthnance, according to their scales and context. Some of the processes have already been studied in some detail. An intensive observing program at Astoria Canyon showed details of the interaction of a time-dependent along-shelf current with the canyon and points to a special role that canyons may play in ocean-shelf exchanges (B. Hickey). Internal Lee waves generated by along-slope flows over small-scale topography show an asymmetry in the propagation characteristics that lead to a transport of mean-flow momentum onto the shelf (S. Thorpe).

Flow separation is important in numerous areas of engineering fluid mechanics. It is also apparent in many nearshore flows and has significant implications for nearshore dispersion. The physics depends on bottom slope, friction, stratification, and rotation. Most of this parameter space has not, however, been explored (C. Garrett). Using the wind-forced barotropic shallow-water vorticity equation, J. Becker examined the dynamics and energetics of western boundary current detachment above a continental margin. Flow separation may also play a role in the deep ocean and constitutes a mechanism by which mixed fluid layers can detach from the boundary and contribute to interior mixing. Flow separation might also be the cause of a wave-like signal observed in sea level records in the Western Pacific. Using GEOSAT altimetric heights, G. Mitchum has tracked this signal all the way back to South Point on the Big Island of Hawaii.

Laboratory Studies

Theoretical studies and numerical experiments are complemented by laboratory studies. S. Allen studied flows that encounter various sorts of obstacles and delineated the linear effects governed by propagation of topographic Rossby waves from nonlinear effects and the influence of stratification on both. G. Ivey studied in detail the turbulent mixing induced by the critical reflection of internal waves at a slope, and S. Thorpe showed how the presence of a sloping boundary affects the transition to turbulence in a stratified shear flow and leads to "twisted" billows. J. Verron performed experiments in the 13-m diameter rotating tank in Grenoble to study rectification in a coastal geometry with an offshore bank. The laboratory results agree qualitatively with simulations from a homogeneous primitive equation numerical model, showing two distinct flow regimes depending on the ratio of the flow oscillation to the background rotation frequency. Overall, these laboratory studies provide detailed and specific insights into topographic effects that might be at work in the ocean.

Rectification Process

The interaction of eddies, waves, or oscillating flows with topography generates mean flows. This rectification process was the topic of the 1989 workshop "Topographic Stress in the Oceans" (Holloway and Müller, 1990, Eos 71, 12). Since then considerable progress has been made, mostly the result of increasingly powerful simulations. When considering the rectification process, a distinction needs to be made between the direct forcing by independently driven eddy processes and the reorganization of the mean flow caused by instabilities (as in the Gulf Stream recirculation). High-resolution experiments with a barotropic shallow water model show that an initial field of random eddies in a basin surrounded by continental margin topography produces a vigorous rectified flow (A. Shchepetkin). Experiments in a similar setting with a three-layer fluid of coarser resolution were performed by E. Chassignet to investigate how well the topographic stress exerted by unresolved eddies can be represented in a coarser resolution model, following statistical mechanical tendencies. Coarse resolution models with parameterized eddy-topography interaction showed improved fidelity when compared with data from a global inventory of long-term current meter observations (G. Holloway).

In a coastal configuration, D. Haidvogel compared five differently formulated numerical models. While rectification of an imposed oscillatory flow occurred in each of the models, specific results differed substantially among the models.

The Surf Zone, Where Topography and Flow Interact

In many circumstances, the topography is given and the flow responds. But there are circumstances when the topography yields. This was impressively documented in a time-lapsed video by R. Holman. It showed the sandbank patterns shifting under the influence of the pounding surf at an Oregon beach over a two year period. Here, flows and topography truly interact with nonlinear feedback loops that are not fully understood yet.

Conclusions

The influence of topography on ocean circulations is greater than previously supposed. Though confident characterization of the dynamic processes is still problematic ambitious observing programs and powerful numerical simulations have caused some striking advances in recent years:

- One of the last frontiers in oceanography, the circulation in deep basins, is being mapped and its dynamics explored by various types of numerical models and ideas from hydraulic control.
- Processes, like internal wave reflection and topographically trapped wave modes, are now recognized to lead to vigorous mixing near slopes. The larger scale consequences of this boundary mixing are being explored.
- While the importance of understanding ocean-shelf exchange processes is increasingly recognized, this remains a daunting subject for laboratory studies, numerical simulations, and comprehensive field experiments.
- The parameterization of topographic stress (rectification), while not yet a fully resolved issue, has seen marked progress since the 1989 meeting as a result of novel approaches based on statistical mechanical tendencies and increasingly powerful numerical simulations.

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