

Large-Eddy Simulation of Flow over Coastal Ridges

E. D. Skyllingstad and H. W. Wijesekera

Oregon State University, Corvallis, Oregon - USA

Abstract. Experiments are conducted with a large-eddy simulation turbulence model examining the effects of bottom obstacles on stratified flow. For obstacles with small width (< 100 m), we find that the formation of a bottom boundary layer greatly limits the transfer of momentum from the flow into internal waves. Increasing the width of the obstacle leads to a stronger internal wave response, with intermediate width obstacles having significant lee waves and relatively wide obstacles generating a single wave mode with a broad region of strong flow on the downslope portion of the obstacle. The results suggest that small-scale obstacles are probably not important for internal wave momentum drag, however, for obstacles approaching ~ 500 m width, wave drag may be significant.

Introduction

Boundary processes are key elements in the global ocean circulation. At the surface, momentum and heat fluxes define the main ocean gyres and the thermohaline circulation. Momentum is lost at the bottom of the ocean through drag produced by aerodynamic surface roughness and by pressure form drag as flow passes over obstacles. In the abyssal ocean, tidal flows over ridges and valleys can generate significant mixing through baroclinic modes. Mixing and significant drag are also generated in coastal waters where tidal and large-scale currents interact with bottom topography. For example, *Nash and Moum* (2001) describe the effects of flow over a small coastal bump, which causes increased drag and the generation of turbulence. Their observations suggest that the scale of the bump leads to a hydraulically controlled flow with a strong downstream jet and subsequent hydraulic jump. Other observations of tidal forced flows over sills, for example *Farmer and Armi* (1999) indicate a similar response, but with a trailing lee wave system more in line with atmospheric mountain wave phenomena. In both cases, turbulence is produced in the lee of the obstacle. However, the formation of lee waves may indicate that some of the internal wave energy produced by the flow obstruction is channeled into dispersive waves rather than into a strong nonlinear jump.

Although observations have yielded much about flow over bottom obstacles, only a few well-documented cases have been thoroughly studied. Detailed maps of coastal bathymetry show significant small-scale variations in bottom terrain along the continental margins that may have an important impact on the momentum budget and vertical mixing. Here, we examine the behavior of flow over obstacles using a large-eddy simulation (LES) model that has been modified to simulate changes in depth from bottom features. Experiments are performed using a periodic channel with a length many times the obstacle width so that disturbances generated by the obstacle do not overly affect the upstream conditions. Details of the model and basic simulations can be found in *Skyllingstad and Wijesekera* (2003). Work presented in this paper is an extension of the original cases and focuses on the effects of obstacle width on the flow response.

Flow Parameters

Observations of stratified flow behavior near coastal bottom features show significant localized momentum flux and mixing associated with internal waves and jumps forced by the flow passing over the obstacle. Assessing the importance of bottom forced mixing requires a better knowledge of the processes and ambient conditions that produce these effects. A number of dimensionless parameters determine how

obstacle flow will behave depending on the water depth, H , obstacle height, h , obstacle half width, a , flow velocity, U , and stratification as measured by the Brunt Vaisala frequency,

$$N = \sqrt{\frac{g}{\rho} \frac{\partial \rho}{\partial z}}.$$

Internal waves generated by obstacles have a vertical structure determined by the mode number,

$$K = \frac{HN}{\pi U}.$$

These waves can amplify and break depending on the dimensionless obstacle height, $\tilde{h} = hN/U$, and the value of K . Roughly speaking, flow stability is reduced as h increases and for K values close to integers. Formation of a hydraulic jump or lee waves (also referred to as a transitional flow) is determined in a large part by the dimensionless obstacle width, Na/U . For Na/U greater than ~ 10 - 20 , lee waves are suppressed and the flow generates a hydraulic jump. Small obstacles, on the other hand, generate stronger lee waves, which disperse energy downstream from the obstruction.

Bottom Drag

Flow behavior is also determined by the dynamics of the bottom boundary layer generated through surface roughness. Formation of a bottom mixed layer can have a profound impact on the internal wave response of the flow. For example, Figure 1 shows two simulations of a flow with $K = 1.12$ using an obstacle height defined as

$$h = \frac{h_{\max}}{1 + (x/a)^2}$$

where $a = 15$ m is the obstacle half width. In the top case, a free-slip bottom boundary conditions is imposed, whereas in the bottom plot a surface roughness length of 0.001 m is applied. Bottom drag in the latter case causes a bottom boundary layer to form, creating a region of slower moving fluid near the bottom and effectively reducing the height of the obstacle relative to the original case. Bottom friction also reduces the amount of kinetic energy available for wave formation and changes the stratification, which alters the basic flow characteristics.

The example given in Figure 1 is for a relatively narrow obstacle having small Na/U , suggesting that

small bottom features may not require special parameterizations for large-scale models. But, as observations show, larger scale features are known to generate strong internal waves, jumps and mixing events. To examine how obstacle width affects the stratified flow response, we performed a series of experiments using flow conditions with $N = 0.015$ s⁻¹ and $U = 0.2$ m s⁻¹, yielding $K = 1.07$. Water depth was set to 45 m with an obstacle height of 9 m so that the flow would generate a nonlinear response, assuming the bottom boundary layer did not extract too much energy or alter the background flow conditions significantly. Three obstacle half widths were considered, 150, 225, and 375 m, yielding Na/U ranging from ~ 11 to ~ 28 . Simulations were conducted using an approximately two-dimensional domain with 16 grid points in the cross stream direction and 60 grid points in the vertical. Domain size in the streamwise direction varied depending on the obstacle width increasing from 2400 m to 4800 m from the smallest to largest obstacle. In each case the bottom roughness length is set to the same value (0.001 m) as the bottom boundary layer case presented in Figure 1.

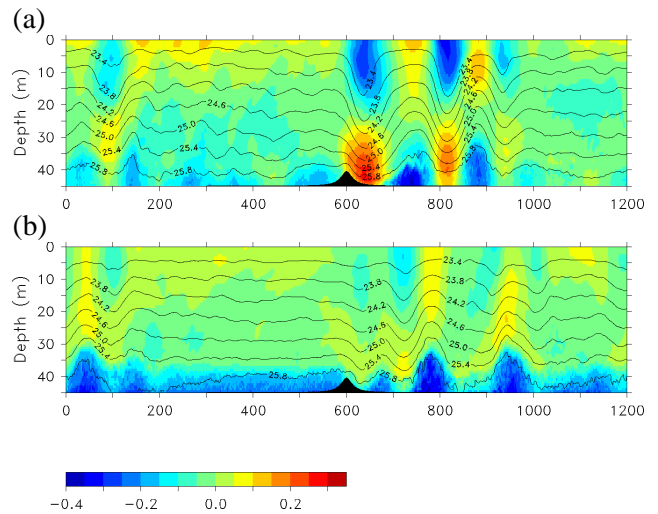


Figure 1. Vertical cross sections of velocity and potential density for a (a) free slip bottom and (b) rough bottom with roughness length of 0.001 m.

Cross-section plots of the obstacle flow and density structure are shown in Figure 2 after four hours of simulated time for the 150 and 375 m cases. Two features stand out in the simulations. First, the formation of a strong transitional flow is evident in both of the cases, even though bottom roughness is

applied in each case. This result differs from the narrow obstacle case presented in Figure 1, suggesting that small obstacles may not have as much influence on momentum flux and formation of turbulent mixing.

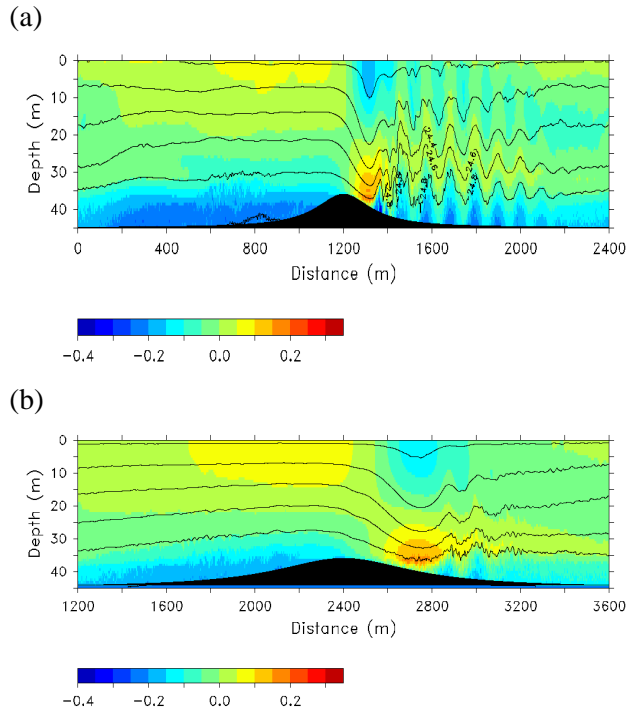


Figure 2. Cross section of velocity (shaded) and potential density (contours) after 4 hours for an obstacle (a) 150 m wide and (b) 375 m wide.

The second point to make about Figure 2 is the significant influence that obstacle width has in controlling the wave response of the flow. With a 150 m wide obstacle, a train of trailing lee waves is produced, with a small region of increased downslope current just downstream from the obstacle summit. In contrast, the 375 m obstacle has not developed significant trailing lee waves and has a larger region of strong downslope currents. None of the cases generate a strong hydraulic jump structure as observed by *Nash and Moum (2000)* and *Farmer and Armi (1999)*. However, in both of the observed cases, stratification was not uniform upstream from the obstacle, which may have naturally lead to a better defined jump condition. Also, the width of the obstacles in both observed cases was $O(1 \text{ km})$, which would have further emphasized the hydrostatic response noted in the 375 m case presented here.

Summary

In summary, we find that flow passing over obstacles is strongly influenced by the obstacle scale. For conditions favoring a transition flow, bottom friction can cause significant flow disruption, preventing strong internal waves and wave breaking. The effects of bottom friction are reduced as the width of the obstacle is increased. Obstacle width also plays a role in determining the downstream behavior of the flow. In general, narrow obstacles have a stronger nonhydrostatic response with trailing lee waves. Wider obstacles generate a more hydraulic response without lee waves, but with a jump condition downstream from the obstacle.

These results suggest that bottom features with scales greater than $\sim 100 \text{ m}$ can significantly increase bottom drag and provide sources of mixing that would otherwise not be apparent. Flow response occurs over time periods within the tidal cycle, indicating that coastal regions need to be considered when calculating total ocean mixing and drag in ocean circulation models. For smaller scale obstacles, the formation of a turbulent bottom boundary layer prevents a strong pressure form drag. Consequently, small-scale objects can likely be combined with parameterized bottom friction in large-scale circulation models.

Acknowledgments. This work was supported by the Office of Naval Research, grants N00014-98-1-0113 and N00014-01-1-0138.

References

- Farmer, D. M., and L. Armi, Stratified flow over topography: The role of small scale entrainment and mixing in flow reestablishment. *Proc. R. Soc. London, Ser. A.*, 455, 3221-3258, 1999.
- Nash, J. D., and J. N. Moum, Internal hydraulic flows on the continental shelf: High drag states over a small bank, *J. Geophys. Res.*, 106, 4593-4612, 2001.
- Skyllingstad, E. D., and H. W. Wijesekera, Large-eddy simulation of flow over two-dimensional obstacles: High drag states and mixing, *J. Phys. Oceanogr.*, accepted, 2003.

