Topographic Rossby Waves in a Z-level ocean model

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Topographic Rossby waves (TRW) play an important role in the ocean dynamics in regions where the slope of the bottom topography is sufficiently large so as to dominate the β-effect. TRW propagate signals in the ocean along the slopes over large distances [*Oey and Lee*, 2002]. *Pacanowski and Gnanadesikan* [1998] suggested that when the bottom slope is less than the grid cell aspect ratio (Δz/Δx) in a numerical ocean model with a Z-level vertical coordinate, the model does not accurately resolve topography leading to an inaccurate simulation of topographic waves with a modified dispersion relation. It is important to better understand the consequences of the modelers' choices of vertical grids since coarse vertical resolution ocean models can alter the rate and direction of propagation of waves. In this study we examine the ability of Z-level models to accurately simulate topographic waves by conducting model experiments with σ-level (terrain following) and Z-level vertical coordinate systems with different vertical resolutions.

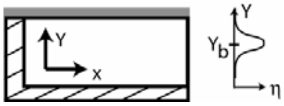

Figure 1. *Model domain. The impulse is imposed at the eastern boundary. Dashed region is a "sponge" domain.*

A long barotropic shelf in the northern hemisphere with variable depth H on an *f*-plane is considered (Figure 1). The width of the shelf is 400 km, and the depth linearly increases offshore from 0 to 400 m. The bottom slope (α) is $1\mathrm{x}10^{-3}$ which is sufficiently large $\left(|\nabla H| > H/R \tan\phi_0\right)$ to dominate the β-effect (R is radius of the Earth) [*LeBlond and Mysak*, 1978]. The horizontal grid spacing is 5 km. The dashed area is a sponge region with a linearly increasing spatial step to prevent the open boundaries from interfering with the solution within the interior of the domain. The simulations are performed with the Navy Coastal Ocean Model (NCOM) [*Martin*, 2000]. The model is initialized at rest and integrated for 20 days. Forcing is applied at the eastern open boundary in the form of a Gaussian sea level anomaly with a dynamically consistent velocity field (Figure 1): $\eta = \eta_0 \exp\left(-\left((y-y_b)^2 \big/ 0.0225\right)\right)$, where $\eta_0 = \begin{cases} 0.18 \cdot \exp\left((day-5)^2 \big/ 2\right), & day < 9 \\ 0, & otherwise \end{cases}$, y_b=0.5 is the offshore location of the maximum normalized by the shelf width. The control run is performed with 2 σ levels which, for given slope, realistically resolve the topography (Figure 2a). Then several runs using Z-levels with the number of levels varying from 3 to 40 are performed. Models with coarse vertical resolution significantly alter the topography (Figure 2) and affect the characteristics of topographic waves initiated by the impulse (Figure 3). With very coarse vertical resolution (3 Z-levels) the bottom topography is approximated by several wide steps (Figure 2b) with widths comparable to the barotropic Rossby radius (L=150 km, Ro ~ 600 km). The model produces double Kelvin waves trapped by the partial vertical walls [*LeBlond and Mysak*, 1978] (Figure 3b) artificially created by vertical discretization of the topography. As the vertical resolution increases, double Kelvin waves can not be supported by

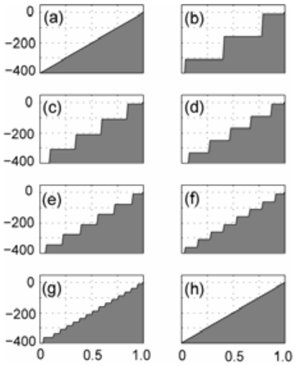

Figure 2. *Bottom topography in model experiments with σ-levels (a) and Z-levels (b through h). The number of Z levels increases from (b) to (h): 3, 4, 5, 6, 8, 16, and 40. The ordinate is depth (m) and the abscissa is the offshore distance divided by shelf width.*

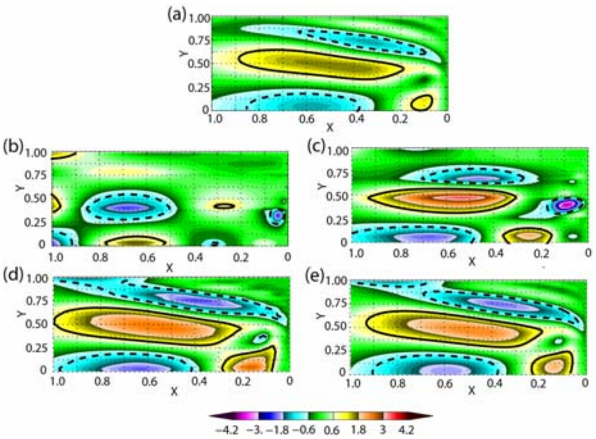

Figure 3. *Snapshots of simulated topographic waves. SSH anomalies (cm) on the 13th day of integration. Solid line contours are drawn at 1 cm, and dashed line contours are -1 cm. The abscissa is the along-shelf distance normalized by the length of the domain (1000 km). The ordinate is as in Figure 2. (a) σ-level model; (b) 3 Z-levels; (c) 5 Z-levels; (d) 16 Z-levels; (e) 40 Z-levels. Note that (d) and (e) are similar to (a).*

narrow steps and the solution approaches propagating TRW similar to those simulated with the σ-level model (compare Figures 3b to 3e with 3a).

Hovmöller diagrams of the crosscorrelation coefficients of the sea surface height (SSH) anomalies along the shelf (Figure 4) are used to estimate the phase velocity of the topographic waves. The crosscorrelation coefficients are calculated between the SSH on the day after the forcing at the eastern boundary has died out and the system reaches quasi-geostrophic balance (8-10th day of the integration) and daily SSH after that day. The estimated phase speed of the TRW simulated with the σ-level model is ~2.5 km/hour. Comparison of the diagrams for the Z-level models with course resolution (Figures 4b – 4e) reveals an obvious and significant modification of the wave. Starting from the model with 8 Z-levels, the solution approaches the σ-level solution (compare Figures 4f-4h with 4a).

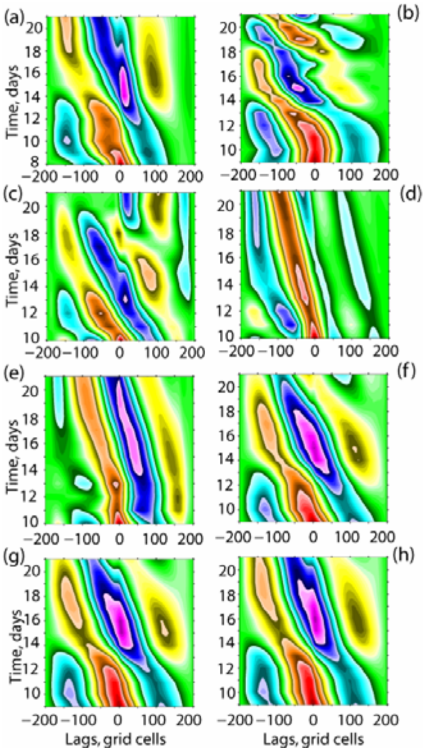

Figure 4. *Hovmöller diagrams of the SSH autocorrelation for 8 experiments using σ-levels (a) and Z-levels (b through h) shown in Figure 2. Note that the solutions using Z-levels approach the σ-level solution (a) as the number of Z-levels increases.*

The obvious conclusion is that Z-level models can accurately reproduce TRWs if the bathymetry is well resolved in the model. Poor vertical resolution leads to an unrealistic representation of the bathymetry, which initiates different waves with different dispersion relations resulting in errors of signal propagation in the model. Future research will focus on establishing the necessary criteria for the resolution of bathymetry in Z-level models for properly simulating TRW. From preliminary results it can be noted that the ratio between the grid cell aspect ratio to the topographic slope discussed earlier may not be a *necessary* criteria for a Z-level model's ability to reproduce TWS. It was previously understood that this ratio should be 1 (as in σ-level models) which necessitates that the number of vertical grid points in most typical Z-level model configurations must be dramatically increased. However these results suggest that the ratio does not need to be 1 (Figures 5). For this domain, even 8 Z levels (with a grid cell aspect ratio 10 times larger than the bottom slope) seem to be enough to reproduce TRW similar to the σ-level model (Figure 4).

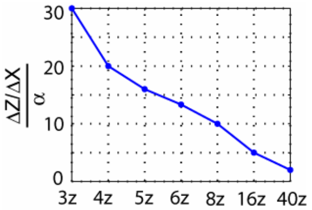

Figure 5. *Ratio of the grid cell aspect ratio and bottom slope for the models with different number of Z levels.*

Acknowledgements

This project was sponsored by the Office of Naval Research Secretary of the Navy grant to James J. O'Brien, and by the NASA Office of Earth Science. Computer time was the FSU Academic Computing and Network Services.

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