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Basin Mode Internal Tides

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Abstract

The Regional Ocean Modeling System (ROMS) is used to test the hypothesis that the equilibrium tide can excite coupled barotropic and baroclinic basin modes in large basins and result in large-amplitude internal tides, dependent on parameters such as basin-scale bathymetry and stratification. The domain is an idealized, stratified, mid-latitude rotating ocean basin with a horizontally uniform continental shelf and slope around the deep basin, with horizontally uniform stratification, forced by the equilibrium M_2 tide. Different stratifications are compared. Results show internal tide standing basin modes and coastally trapped modes. The baroclinic response is strongly dependent on stratification, with some stratifications having a near resonant response. Stratification affects internal tide wavelength scales, amplitudes and their distribution, and alongshore propagation distance of coastally trapped modes. Perhaps some of the spatial variability and temporal intermittency observed in coastal internal tides is due to spatial and temporal (from changes in stratification) variability in the basin mode response.

1 Introduction

We are all familiar with the excitation of normal modes in some way. In playing a musical instrument, normal modes of strings, surfaces, or air cavities are excited. Blowing across the opening of an empty drink bottle can excite a normal mode of the air cavity, making it whistle at a distinct frequency. And simply splashing water in a bathtub excites the normal modes of the basin. If the water is sloshed back and forth at a regular frequency and that frequency happens to be close to that of a normal mode of the tub, then a large amplitude response can occur, splashing water out of the tub. Just like the bathtub, any closed basin will have normal modes. The response of a basin to a periodic forcing can be described as an expansion over the basin's normal modes, oscillating at the forcing frequency. A mode will have a larger response if its frequency is close to the forcing frequency and if its spatial pattern fits that of the forcing.

Barotropic tides have been described as the excitation of normal modes of the world oceans in a series of papers, showing that observations of barotropic tides are consistent with some of these modes [*Platzman*, 1975, 1978, 1984a, 1984b; *Platzman et al.*, 1981]. For example, the large-scale cyclonic California amphidrome, which yields the observed M_2 tide propagating northward along the west coast of North America, is directly related to the structure of an individual Kelvin wave normal mode with a 15.5-hour period that is non-resonantly forced at the M_2 tidal period [*Platzman et al.*, 1981; *Platzman*, 1984b].

When a basin is stratified, its normal modes become more complicated, with coupled barotropic and baroclinic normal modes. The stratification introduces internal waves, adding smaller spatial scales to the modes, and bathymetric variability also results in variability in spatial scales of the modes. *Winant* [2010] shows that the excitation of basin modes can explain large amplitude internal tides observed in some small basins. His free-surface, coupled barotropic/baroclinic, two-layered model forced by the co-oscillating tide for an idealized domain representing the Strait of Juan de Fuca-Strait of Georgia system resulted in a cross-channel internal seiche mode response that is similar to internal tide observations by *Martin et al.* [2005].

These works showing that barotropic and baroclinic tides can be thought of as three-dimensional, whole system responses motivated us to hypothesize that the equilibrium tide can excite coupled barotropic and baroclinic basin modes in large basins and result in large-amplitude internal tides, dependent on parameters such as basin-scale bathymetry and stratification. Here, we use the Regional Ocean Modeling System (ROMS) to test our hypothesis using an idealized model. In section 2, we will describe the model domain and runs performed, in section 3 we will present model results, and section 4 will include discussion and conclusions.

2 ROMS Model Runs

The model domain is an idealized mid-latitude ocean basin on an *f*-plane at 45° N, with an alongshelf-uniform continental shelf and slope around a deep basin (Figures 1 and 2a). The basin is stratified with a profile that is horizontally uniform and nearly two-layered, and multiple runs were performed, each with the same pycnocline thickness and depth, but with different stratification strengths across the pycnocline (Figure 2b). The model is forced by the equilibrium M_2 tide as a body force applied in the pressure gradient term of the momentum equations. It is a wave that propagates from east to west over the entire basin, with a 12.42-hour period, a wavelength of 14,153 km, and a slight decay in amplitude in the positive y-direction. The forcing amplitude is kept small (0.1 m) so as to keep the response approximately linear. Models were run for 60 days, with analyses performed on the last 20 days of model output.

The normal modes of a basin will change with changing stratification, so the different model runs with different stratification are a way to demonstrate the tuning/detuning of large amplitude normal mode responses of the domain to the M_2 tide forcing and to explore how the response changes with variations in stratification.

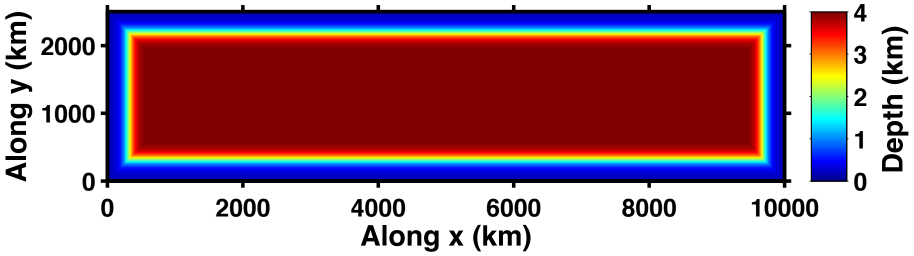

Figure 1: Plan view of ROMS model domain, with colors representing depth. Basin is 10,000 by 2,500 km, with 10-km horizontal grid spacing, and is on an *f*-plane at 45° N.

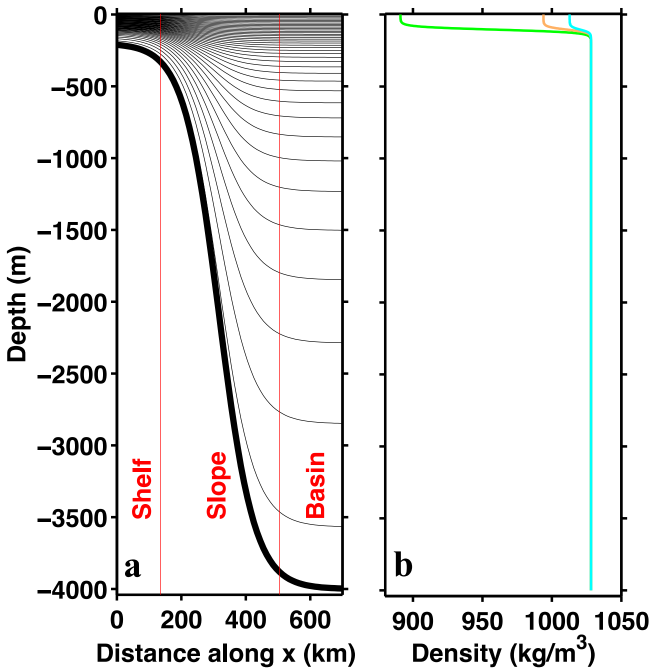

Figure 2: (a) Side view of bathymetry (bold line) with 40 vertical terrain-following coordinates. Shelf (~135 km wide, 210 m deep), slope (~370 km wide), and basin (4,000 m deep) regions are indicated. (b) Three of the stratifications used, with the same pycnocline thickness (~100 m) and depth (105 m), but different minimum densities and thus stratification strengths.

3 Model Output Results

From the output of the different model runs, the maximum amplitude of interface (defined as the center of the pycnocline) displacement for each stratification shows a series of peaks in the response amplitude (Figure 3).

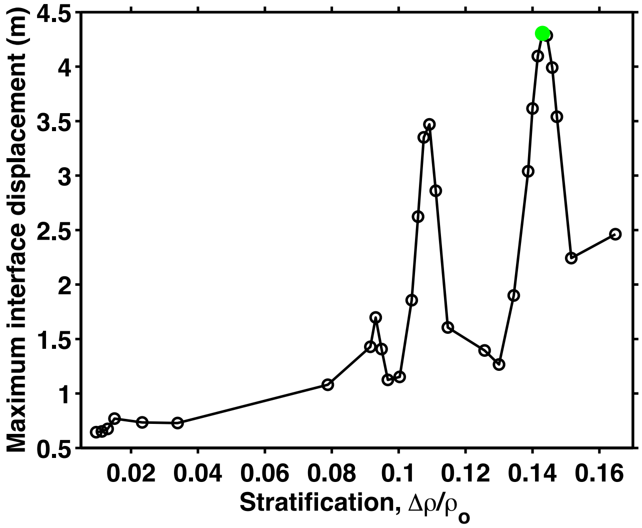

Figure 3: Maximum amplitude of the harmonic fit of internal interface motions to the M_2 frequency for several model runs with different stratifications. Green colored dot corresponds to the result for the strong stratification plotted in a green line in Figure 2b.

The stratifications that have the large-amplitude internal tide responses, such as the one plotted in green in Figures 2b and 3, likely have one or more basin modes with frequencies that are near resonance with the forcing frequency and with spatial patterns that match up with that of the forcing. As the stratification strength changes, the amplitude of the response can change greatly. For the remainder of section 3, results from the model output for the strong stratification plotted in green will be presented and described, and in section 4, the results for other stratifications will be briefly discussed.

3.1 Sea Surface and Internal Response

The sea surface and interface motions were explored by performing harmonic fits to the M_2 frequency (Figure 4). The sea surface response has three amphidromes around which barotropic Kelvin wave-like motions propagate, with smaller spatial scales introduced by stratification (Figure 4, upper panel). These smaller spatial scales are more visible in the interface motions, in which it is also apparent that there are smaller spatial scales on the shelf than in the deep basin (Figure 4, lower panel). For this stratification and basin, the internal response was much larger amplitude than the sea surface response.

In the deep part of the basin, the internal tide is a standing basin mode. On the shelf, the internal tide has both standing modes and propagating modes (shown in section 3.3), and these are of different spatial scales (shown in section 3.2). The internal response amplitude varies spatially, with some regions generally having smaller amplitude than others (e.g. from $x = 0$ to 2000 km versus from $x = 2000$ to 4500 km), in part related to the three amphidromes. The largest amplitude response for this stratification is located on the shelf.

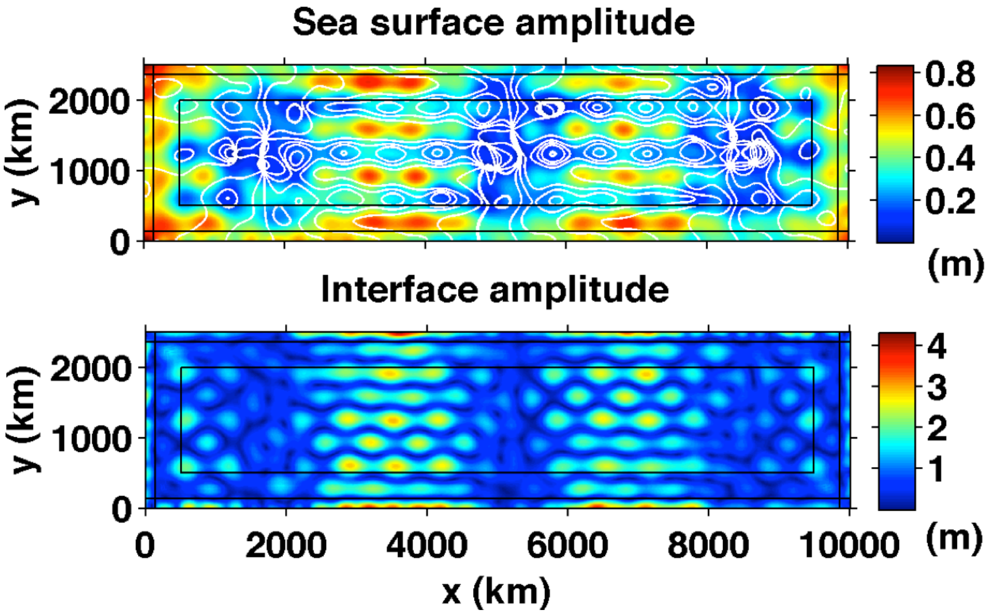

Figure 4: Amplitudes for harmonic fits of sea surface and internal interface motions to the M_2 tide forcing frequency for the stratification plotted in green in Figures 2b and 3. Phase lines for the sea surface result (white lines) show three amphidromes with barotropic Kelvin wave-like motions around the basin. Black lines delineate shelf, slope, and basin regions. Note the different color axis limits for the two panels.

3.2 Internal Spatial Scales on the Shelf, Slope, and Basin

To further explore the spatial scales of the internal tide response, one-dimensional wavenumber power spectra of the interface, along the *x*-direction, were made for the shelf, slope, and deep basin regions (Figure 5). This revealed a range of small wavenumbers that were common to all regions of the domain (blue box) and a range of larger wavenumbers that were mainly confined to the shelf region. The scales are consistent with expected linear internal tide wavelengths for the deep basin and with expected coastally trapped internal tide wavelengths. The wide spread of wavenumbers for the basin modes is due to the modes propagating at different angles in the basin and the fact that this is only shows wavenumber *k*. For this model run, the amplitude of the shelf-confined scales is comparable to that of the basin modes.

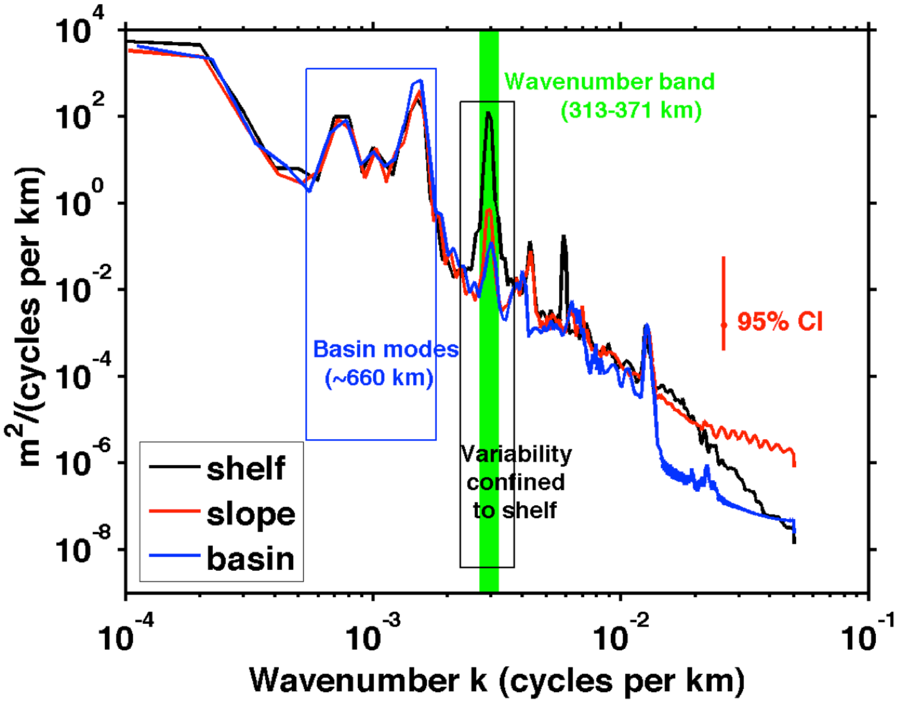

Figure 5: 1-D wavenumber power spectra of the interface, along the *x*-direction, for the shelf, slope, and basin regions of the results for the stratification plotted in green in Figures 2b and 3. The blue box shows scales common to all regions of the domain; the black box shows scales confined to the shelf region.

3.3 Variability Confined to the Shelf

The larger wavelength internal tide standing wave behavior over the shelf is apparent by watching interface motions through time. Band-pass filtering the interface motions spatially in the *x*-direction over the shelf wavenumber band (Figure 5, green band) reveals that these internal tide shelf scales are a superinertial coastally trapped wave with a quarter-wavelength fitting over the shelf in the cross-shelf direction, propagating a long distance (almost the entire 10,000-km basin length) along the shelf (Figure 6).

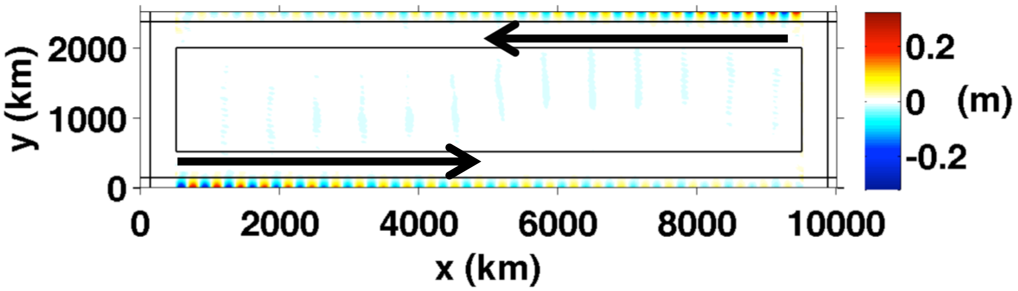

Figure 6: A time-step of interface motions that were band-pass filtered spatially along *x* over the shelf wavenumber scales in the green band in Figure 5. Arrows show direction of propagation of coastally trapped waves. Note that the results for the eastern and western ends of the domain are not included, as to not include edge effects of the filtering. Black lines delineate shelf, slope, and basin regions. Note that the apparent amplitude depends on the width of the band-pass filter.

4 Discussion and Conclusions

The results presented show internal tide standing modes in the deep basin and both standing and alongshore propagating coastally trapped internal tide modes on the shelf. The results were similar for other stratifications (not shown), with the amplitudes and their regions of largest response, the wavelength scales (smaller for weaker stratification), and the trapping distances for alongshore propagation of coastally trapped internal tides strongly dependent on stratification. We interpret the strong dependence of amplitude on stratification (Figure 3) as the tuning/detuning of near resonant normal mode responses of the domain to the M_2 tide forcing.

We are working on a separate linear modeling analysis (analytical and numerical) to understand the response in terms of normal modes. The analysis allows us to calculate basin normal modes for simple basins and their excitation amplitude due to a forcing, allowing us to efficiently explore the tuning/detuning of resonant responses through wide ranges of the relevant parameters. Though the linear model is not as complicated as the ROMS domain, results have shown patterns similar to those of the ROMS work: series of peaks in maximum response amplitude as a pertinent parameter is varied; different spatial scales due to bathymetric variability; variability in regions of large and small amplitude response.

The ROMS domain and stratification used were chosen based on computational efficiency and for ease of comparison with a linear model. The domain is very large, limiting the grid resolution that can be run efficiently. The shelf width and stratification were chosen to be able to fit a quarter wavelength internal tide over the shelf in the cross-shore direction and to resolve it. Most of the stratifications used are larger than physically possible, but even the weakest stratification run had a basin mode internal tide response qualitatively similar to that shown. The almost two-layer stratification was chosen because we will be using two-layered stratification in the linear analysis.

In the real ocean, stratification changes temporally. Therefore, the normal modes of a basin also change temporally. While the unrealistically large stratification shown here does produce an internal tide basin mode wavelength that could propagate across the basin in about a week, which is a period of time over which stratification of a basin might remain relatively constant, a more realistic internal tide wavelength could take about a third of a year to propagate across a 10,000-km basin. Therefore, it would take about a third of a year for the basin mode response to set up in the deep basin. It is unlikely that the stratification would remain constant over that time, meaning the deep basin mode internal tide response likely could not develop in such a large basin. However, the shelf modes, with less distance to propagate, might still be able to develop in a shorter time, making the problem still applicable to large basins, and certainly to smaller basins, such as perhaps the Gulf of California.

Another implication of the temporal change of stratification changing the basin modes is that there will be temporal intermittency in basin mode internal tide response. The results also show spatial variability in the amplitude and structure of the basin mode internal tide response, which will also change temporally with stratification. Observations of coastal internal tides have shown temporal and spatial variability. For example, *Lerczak et al.* [2003] found temporal intermittency of the coastally trapped, alongshore propagating superinertial internal tide observed on the continental margin off of Mission Bay, CA, that was not related to the spring/neap tide cycle. *Alford et al.* [2006] identified east- and west-bound, alongshore propagating superinertial internal tides in Mamala Bay, south of Oahu, HI, that interfere with each other to yield an approximately standing wave pattern. The phases and magnitudes varied relative to astronomical forcing. They attribute this variability to remote generation, with the timing modulated by background stratification between the sources and the bay. Perhaps the temporal intermittency and spatial variability of basin mode internal tide responses can explain some of the temporal and spatial variability seen in observations of coastal internal tides.

Further work with linear modeling and ROMS modeling will be performed to provide insight on space and time scales of basin mode internal tides and thus where and when basin mode internal tide response can be applicable and important in the ocean.

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