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LONG-TERM GOALS

The long-range goals of this project are to understand the environmental factors that define the level of internal wave activity in the littoral oceans and to develop re-locatable models capable of predicting these levels. The hypothesis is that energy due to internal tides generated through interactions with complex coastal topography is both predictable, using high-resolution primitive equation numerical models, and responsible for setting energy levels of the broader-frequency internal wave spectrum.

OBJECTIVES

This project seeks to document the nature of internal wave spectra in the littoral ocean environment around Monterey Bay using existing moored velocity time series and simulated coastal time series produced by a three-dimensional, primitive equation numerical model with realistic bathymetry forced by tidal-period sea level oscillations. Project goals include the desire to establish a practical and relocatable modeling framework that can be used to predict littoral internal wave statistics for any other coastal region similarly dominated by baroclinic processes.

APPROACH

This project builds on the dissertation work of LCDR Emil Petruncio (1996). A key person involved with this project in addition to the principal investigators is José Eduardo Goncalves, a Ph.D. candidate from the University of Sao Paulo, Brazil, who is working on the numerical simulations as part of his dissertation research. The approach taken is two-pronged: A primitive equation numerical model, the Princeton Ocean Model (POM), is being utilized in a coastal setting where detailed bottom topography and in situ current observations are available. In particular, observations of the spatial variability of the internal tide in and around Monterey Submarine Canyon—from moored observations at depth and High Frequency radar observations at the surface—are being used to validate the ability of the numerical model to reproduce the current patterns. The model is initialized with high resolution side-scan bathymetry and observed stratification over a 100 km x 100 km domain with 1 km resolution and 30 levels. The model is forced with tidally varying sea level at the offshore boundary.

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The Monterey Bay region has been chosen for this study for several reasons: 1) dramatic topographic features associated with the Monterey Submarine Canyon are known to produce strong and horizontally variable internal tides, 2) deep-ocean current meter records exist for a large number of sites around the area, including many near-bottom records, and 3) parallel research efforts are underway to sample internal waves and turbulent dissipation along the Monterey Submarine Canyon.

WORK COMPLETED

Efforts this year focused on analysis of recent moored current observations from Monterey Submarine Canyon, final revision of manuscript on internal tide observations, submission of the first manuscript on internal tide simulations using idealized bathymetry, identification of historical current meter records around Monterey Bay from 1988 through the present, and set up and testing of numerical simulations using realistic bathymetry. Publication efforts were coordinated with LCDR Emil Petruncio presently on the CNMOC staff at Stennis Space Center, MS, while test runs of the Princeton Ocean Model numerical code using realistic bathymetry were conducted on the Cray Y-MP at the Naval Postgraduate School.

RESULTS

This project has shown the clear influence of bottom topography on the propagation and amplification of internal waves of tidal period. Both observations and model results represent direct evidence of beam-like propagation of these waves in the coastal environment where the waves exist within a few wavelengths of their generation sites. An extensive article describing in situ observations in and around Monterey Submarine Canyon was published this year in the Journal of Physical Oceanography, while a manuscript describing the model results for the case of idealized canyon bathymetry is under review by the same journal.

We have worked to compile information on current meter moorings in the Monterey Bay area that can be used to look at internal wave spectra and, ultimately, for comparison with numerical model predictions of energy levels as a function of mooring location. Thirty-two individual mooring deployments with current meter records between 1988 and 1998 have been identified along with the present location of the data. The locations of these moorings relative to the bathymetry around Monterey Bay are shown in Figure 1. The mooring locations span a wide range of depths and appear to cover a number of internal tide regimes.

A recent record from a bottom-mounted ADCP deployed at site BB in 333 m water depth in the axis of the canyon shows a dramatic variation from deep-ocean internal wave characteristics. Kinetic energy spectral densities from these data are shown in Figure 2 for bins 12 m and 112 m above the bottom. These are compared with predictions from the G-M model for open ocean internal waves using buoyancy frequencies observed at the measurement depths. The near-bottom internal waves are an order of magnitude more energetic than the G-M predictions. They are also 3 to 5 times more energetic than the internal waves measured just 100 m above them. This bottom intensification is expected for the internal tide in the Monterey Canyon, but these results show a similar enhancement across the internal wave band. Furthermore, strong peaks at the frequencies of the non-linear overtides support the notion that energy in the internal wave band is being fed by the strong internal tides at the low-frequency end of the band.

Figure 1. Locations of current meter moorings around Monterey Bay between 1988 and 1998.

A revised POM grid for Monterey Bay has been developed that is rotated about 30 deg counterclockwise from north in order to minimize grid points over land and, more importantly, to align the offshore open boundary parallel to shore. This latter trait allows us to force the model in the manner employed by Petruncio (1996) using sea level forcing at tidal periods on the offshore boundary to produce the barotropic forcing that subsequently interacts with the bathymetry and produces a heterogeneous field of internal tidal waves. The rotated grid has a horizontal resolution of one kilometer with 113 x 113 cells and 30 vertical levels.

An important assessment of the performance of this sigma-coordinate-type model in the presence of steeply sloping bathymetry is the magnitude of the error currents that are generated under stratified but unforced conditions. For the extreme bathymetry variations around Monterey Bay these errors can be large. Figure 3 shows the errors after five days of model integration. In the deep waters errors reach 50 cm/sec. However, the largest sigma-coordinate errors in the slope and shelf regions are less than 5 cm/sec, even along the extreme slopes of the Monterey Submarine Canyon. These results show that it should be possible to map the variable intenal tide currents expected in the forced runs. It may be desirable to “fill-in” the model depths below 2500 m to avoid the large errors shown in Figure 3.

Figure 2. Kinetic energy spectra for currents observed 12 m and 112 m above the bottom at mooring site BB in the axis of the Monterey Submarine Canyon. For comparison, predicted levels from the open-ocean, G-M model are also shown based on observed buoyancy frequencies.

IMPACT/APPLICATIONS

The likely impact of this project will be a change in the way predictions of internal wave energy are made for the coastal oceans with a much greater role to be played by limited-area, high-resolution numerical model simulations. If successful, a large part of the current variability for an arbitrary portion of the coastal ocean will be predictable using only a knowledge of local bathymetry and stratification combined with a model of global tide elevations.

TRANSITIONS

Our preliminary results have motivated other research groups to investigate the role of submarine canyons in generating strong internal tides. Our long-range goal is to develop a re-locatable model that can be easily applied to any coastal region for which sufficiently accurate bathymetry and stratification data exists to predict the energy levels of the internal wave field given typical tidal forcing. The obvious transition target for this technology are the modeling groups within the Naval Oceanographic Office responsible for assessing environmental parameters for strategic portions of the coastal oceans.

RELATED PROJECTS

Of direct importance to this project is the NSF-sponsored field program of Leslie Rosenfeld, Mike Gregg, and Eric Kunze designed to observe turbulent mixing in and around Monterey Submarine Canyon driven by the observed internal tide. We are also collaborating with Marlene Noble of the U.S.G.S. who has maintained four long-term current meter moorings within our model domain. She is also a co-principal investigator with Leslie Rosenfeld and Cynthia Pilskaln on an ONR-sponsored project that collected moored current meter observations from the axis of the Monterey Submarine Canyon out to depths exceeding 2000 m. With Francisco Chavez of the Monterey Bay Aquarium Research Institute, we are exploiting the several current meter moorings they maintain in the region.

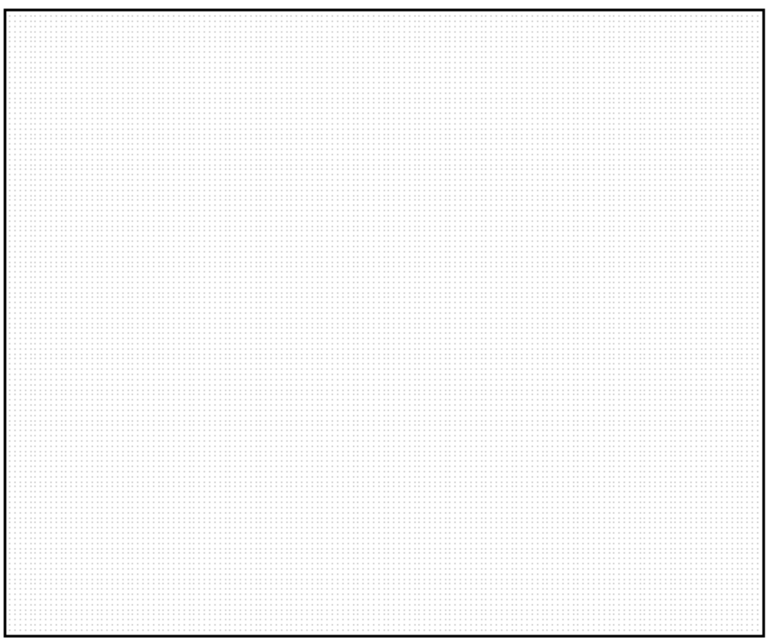

Figure 3. Maximum sigma-coordinate error velocities within the water column. In most cases, the maximum errors are near the bottom.

We are also collaborating closely with several investigators in the use of High Frequency (HF) radars to map surface currents. We are working with CODAR-type HF radar systems deployed around Monterey Bay. At the same time, we are collaborating with John Vesecky of the University of Michigan who has developed and deployed a new Multi-frequency Coastal Radar (MCR) network around Monterey Bay.

Our collaborations on moored observations, HF radar measurements, satellite imagery, and numerical modeling in the Monterey Bay region have recently been solidified under the auspices of the National Ocean Partnership Program (NOPP). The Monterey component of the Program, entitled an Innovative Coastal-Ocean Observing Network (ICON), encompasses many of the data sets and investigators affiliated with this project. Prof. Paduan serves as principal investigator for ICON (see http://oc.nps.navy.mil/~radlab/ICON/).

REFERENCES

Petruncio, E.T., 1996: Observations and modeling of the internal tide in a submarine canyon. Ph.D. dissertation, Dept. of Oceanography, Naval Postgraduate School, 181 pp.

PUBLICATIONS

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