

## A Review of Internal Tide Observations by Acoustic Tomography and Altimetry

Brian Dushaw  
Applied Physics Laboratory  
University of Washington  
1013 N.E. 40th Street  
Seattle, WA 98105-6698  
e-mail: dushaw@apl.washington.edu

Internal-tide waves that travel great distances from their origin at ocean topographic features have been observed in the past several years by both acoustic tomography and altimetry. These waves have consisted of the lowest vertical modes, and their long temporal and spatial coherence is evident.

R. Hendry (1977) using data obtained during the Mid-Ocean Dynamics Experiment (MODE) found the first observational evidence that low-mode internal tides can travel great distances. The MODE array consisted of 16 moorings with thermistors and current meters. Hendry found that the observed  $M_2$  and  $S_2$  internal tides likely originated from the Blake Escarpment, located 700 km to the east. Before the MODE experiment, low-mode internal waves had been expected from theoretical principles to have weak decay (LeBlond 1966), but they were not expected to remain coherent as they traveled distances of many wavelengths in the turbulent ocean environment (Wunsch 1975).

Two decades after the MODE experiment and Hendry's result, data from the 1987 Reciprocal Tomography Experiment (RTE87) in the central North Pacific were used to show that mode-1 internal tides at semidiurnal frequencies propagate at least 2000 km north from the Hawaiian Ridge (Dushaw, et al. 1995). The signals of coherent internal tides were able to be extracted from the complicated ocean environment because of the horizontal and vertical averaging available from the long-range acoustic data. In addition, reciprocal acoustic transmissions were employed so that the thermal and current signals could be separated. The conclusion of Dushaw, et al. (1995) was subsequently supported by Ray and Mitchum (1996, 1997) who used TOPEX/POSEIDON altimetry data to show that spatially and temporally coherent internal-tide waves were radiating from the Hawaiian Ridge. The analysis of Ray and Mitchum consisted of tidal analyses of the altimeter timeseries at points along the altimeter tracks to determine harmonic constants at those points, followed by a high-pass filter along the tracks to eliminate wavelengths greater than about 400 km. The altimetry data have also been used to obtain global estimates of baroclinic tide energies, e.g., Kantha and Tierney (1997) found that globally the internal tides carry 520 GW of power. However, because the TOPEX/POSEIDON altimeter samples the half-day-period tidal variability at 10-day intervals, these observations of the internal tide probably significantly underestimate the tidal variability (Kantha and Tierney 1997). The 1-2 cm internal tide signals in sea surface height are near the limits of detectability by the altimeter; the tidal signals are apparent only because some aspects of the tidal field remain remarkably coherent over the 3-4 year record length of the TOPEX/POSEIDON data.

Using acoustic data obtained from 1000-km range transmissions in the central North Pacific obtained during the SLICE89 experiment, Bracher and Flatte (1997) found similar internal tides apparently emanating from the Gulf of Alaska.

Data from another experiment employing tomography in the Western North Atlantic (the Acoustic Mid-Ocean Dynamics Experiment - AMODE) show that internal tides at diurnal frequencies are trapped in resonance between the Caribbean island arc and the diurnal turning latitude at about 30°N - a round-trip distance of 2200 km (Dushaw and Worcester 1998). The internal displacements of this resonant wave were about 1 meter, which corresponds to surface displacements of order 1 millimeter. These particular waves are not evident in the altimeter data (R. Ray, personal communication 1999).

The observations of these distant traveling internal waves by remote sensing techniques (tomography and altimetry) have been surprising only because nearly all previous observations of internal-tide variability had been made with moored current meter or thermistor instruments which usually suffer from considerable internal-wave noise. For example, Dushaw et al. (1997) show that harmonic constants for the barotropic tide derived from historical current meter records are unreliable measurements of the tidal currents. It is not surprising, therefore, that the noisy data collected from a few points during an experiment have failed to show the large-scale coherence that evidently occurs in the low-mode internal tides.

Many questions concerning these waves remain unanswered. The decay mechanisms of these

distant-travelling waves is presently unknown, but this decay presumably occurs by such mechanisms as bottom friction or a nonlinear cascade to higher wavenumbers (Hendershott 1981). Even the decay scale for the low-mode internal tides is unknown; this scale is apparently  $O(1000 \text{ km})$  or greater. What is the ultimate fate of these waves? The role of the tides has recently been re-recognized as a possible source of mixing of the abyssal ocean (Munk 1966, Munk 1997, Munk and Wunsch 1998, Egbert and Ray 2000). Internal tides that are scattered from topography are one possible mechanism for this mixing. In the region around the Hawaiian Ridge, for example, about half of the energy that is dissipated there from the barotropic tide (20 GW) radiates away from the Ridge in the form of these low-mode internal waves (Egbert and Ray 2000, Merrifield et al. 2000). It is apparent that these waves carry energy, presumably energy available for mixing, for at least a few thousand kilometers from the Ridge. What is the importance of these waves to deep-ocean mixing relative to the local tidally-induced mixing at coastlines or mid-ocean ridges?

An objective map of the altimeter data around Hawaii (Dushaw 2001) found that the mode-1 internal tides carry 2 GW of energy from the Hawaiian Ridge, which is considerably less than other estimates of this energy. Ray and Cartwright [2001] obtained an energy estimate of 6 GW by fitting a simple plane wave model to small subsets of the altimeter data. This value was derived using a more careful method than the earlier crude calculation of Ray and Mitchum [1997] which gave 15 GW. The modeling results of Kang, et al. [2000] (5.4 GW, a 2-layer model) and Merrifield, et al. [2001] (9 GW, including all modes) for the Hawaiian Ridge are more consistent with the Ray and Cartwright estimates. The modeling results also compared favorably to the along-track altimeter data. The energy found from the objective map may be too small because the mapping domain did not include the entire Hawaiian Ridge. In addition, Dushaw (2001) showed that the altimeter data is not altogether consistent with a simple traveling wave model, and the data are sometimes internally inconsistent. With such data the objective map will underestimate the energy. The Hawaiian Ocean Mixing Experiment (HOME) [Pinkel et al. 2000] is presently underway to more accurately assess the tidal radiation and dissipation around the Hawaiian Ridge and its effect on ocean mixing.

## References

- Bracher, C., and S. Flatte (1997) A baroclinic tide in the eastern North Pacific determined from 1000-km acoustic transmissions, *J. Phys. Oceanogr.*, **27**, 485–497.
- Cummins, P. F., J. Y. Cherniawsky, and M. G. G. Foreman (2001) North Pacific internal tides from the Aleutian Ridge: Altimeter observations and modeling. *J. Mar. Res.*, **59**, 167–191.
- Dushaw, B. D., B. D. Cornuelle, P. F. Worcester, B. M. Howe, and D. S. Luther (1995) Barotropic and baroclinic tides in the central North Pacific Ocean determined from long-range reciprocal acoustic transmissions, *J. Phys. Oceanogr.*, **25**, 631–647.
- Dushaw, B. D., G. D. Egbert, P. Worcester, B. Cornuelle, B. Howe, and K. Metzger (1997) A TOPEX/POSEIDON global tidal model (TPXO.2) and barotropic tidal currents determined from long-range acoustic transmissions, *Prog. Oceanogr.*, **40**, 337–367.
- Dushaw, B. D., and P. Worcester (1998) Resonant diurnal internal tides in the North Atlantic, *Geophys. Res. Lett.*, **25**, 2189–2192.
- Dushaw, B. D. (2001) Mapping low-mode internal tides near Hawaii using TOPEX/POSEIDON altimeter data, *Geophys. Res. Lett.*, submitted.
- Egbert, G. D., and R. D. Ray (2000) Significant dissipation of tidal energy in the deep ocean inferred from satellite altimeter data, *Nature*, **405**, 775–778.
- Hendershott, M. (1981) Long waves and ocean tides, in *Evolution of Physical Oceanography* (Cambridge, MA: The MIT Press) 292–341.

- Hendry, R. M. (1977) Observations of the semidiurnal internal tide in the western North Atlantic ocean, *Phil. Trans. R. Soc.*, **A286**, 1–24.
- Kang, S. K., M. G. G. Foreman, W. R. Crawford, and J. Y. Cherniawsky (2000) Numerical modeling of internal tide generation along the Hawaiian Ridge. *J. Phys. Oceanogr.*, **30**, 1083–1098.
- Kantha, L. H., and C. C. Tierney (1997) Global baroclinic tides, *Prog. Oceanogr.*, **40**, 163–178.
- LeBlond, P. H. (1966) On the damping of internal gravity waves in a continuously stratified ocean, *J. Fluid Mech.* **25**, 121–142.
- Merrifield, M. A., P. E. Holloway, and T. M. Shaun Johnston (2001) The generation of internal tides at the Hawaiian Ridge, *Geophys. Res. Lett.*, **28**, 559–562..
- Mitchum, G. T., and S. Chiswell (2000) Coherence of internal tide variations along the Hawaiian Ridge. *J. Geophys. Res.*, **105**, 28 653–28 661.
- Munk, W. (1966) Abyssal recipes, *Deep–Sea Res.*, **13**, 707–730.
- Munk, W. (2000) Once again: once again – tidal friction, *Prog. Oceanogr.*, **40**, 7–35.
- Munk, W., and C. Wunsch (1998) Abyssal Recipes II: energetics of tidal and wind mixing, *Deep–Sea Res.*, **45**, 1976–2000.
- Pinkel, R., W. Munk, P. Worcester, B. D. Cornuelle, D. Rudnick, J. Sherman, J. H. Filloux, B. D. Dushaw, B. M. Howe, T. B. Sanford, C. M. Lee, E. Kunze, M. C. Gregg, J. B. Miller, J. M. Moum, D. R. Caldwell, M. D. Levine, T. Boyd, G. D. Egbert, M. A. Merrifield, D. S. Luther, E. Firing, R. Brainard, P. J. Flament, and A. D. Chave (2000) Ocean mixing studied near Hawaiian Ridge. *Eos, Trans. Am. Geophys. U.*, **81**, pp. 545,553.
- Ray, R. D., and G. T. Mitchum (1996) Surface manifestation of internal tides generated near Hawaii. *Geophys. Res. Lett.*, **23**, 2101–2104.
- Ray, R. D., and G. T. Mitchum (1997) Surface manifestation of internal tides in the deep ocean: Observations from altimetry and island gauges, *Prog. Oceanogr.*, **40**, 135–162.
- Ray, R. D. and D. E. Cartwright, Estimates of internal tide energy fluxes from Topex/Poseidon altimetry: Central North Pacific (2001) *Geophys. Res. Lett.*, **28**, 1259–1262.
- Wunsch, C. (1975) Internal tides in the ocean, *Rev. Geophys. Space Phys.*, **13**, 167–182.
- First Published as: Dushaw, B. D., A review of internal tide observations by acoustic tomography and altimetry, Proc. 5th Pacific Ocean Remote Sensing Conf. (PORSEC), Goa, India, 5–8 December 2000, vol. II, 651–652. Revised October 28, 2001.