Tidal Energy Available for Mixing at the Hawaiian Ridge

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Abstract

The tidal energy budget surrounding the Hawaiian Ridge may be divided conceptually into three components: the energy flux convergence of the surface tide, the energy flux divergence of the internal tide, and the loss of energy to turbulent mixing. In order to infer the energy lost to mixing, we use altimetry data and ocean models to estimate the net convergence of the tidal energy flux at eight tidal frequencies (M2, S2, K2, N2, K1, O1, P1, Q1). By generalized inversion of a high-resolution regional barotropic model with TOPEX/POSEIDON altimeter data, we estimate that the barotropic tide loses approximately 22 GW within 250km of the Hawaiian Ridge. The spatial distribution of the energy flux convergence compares favorably with both observations and models of baroclinic conversion. We also report on ongoing data analysis and modeling efforts to estimate the energy flux of internal waves away from the Ridge.

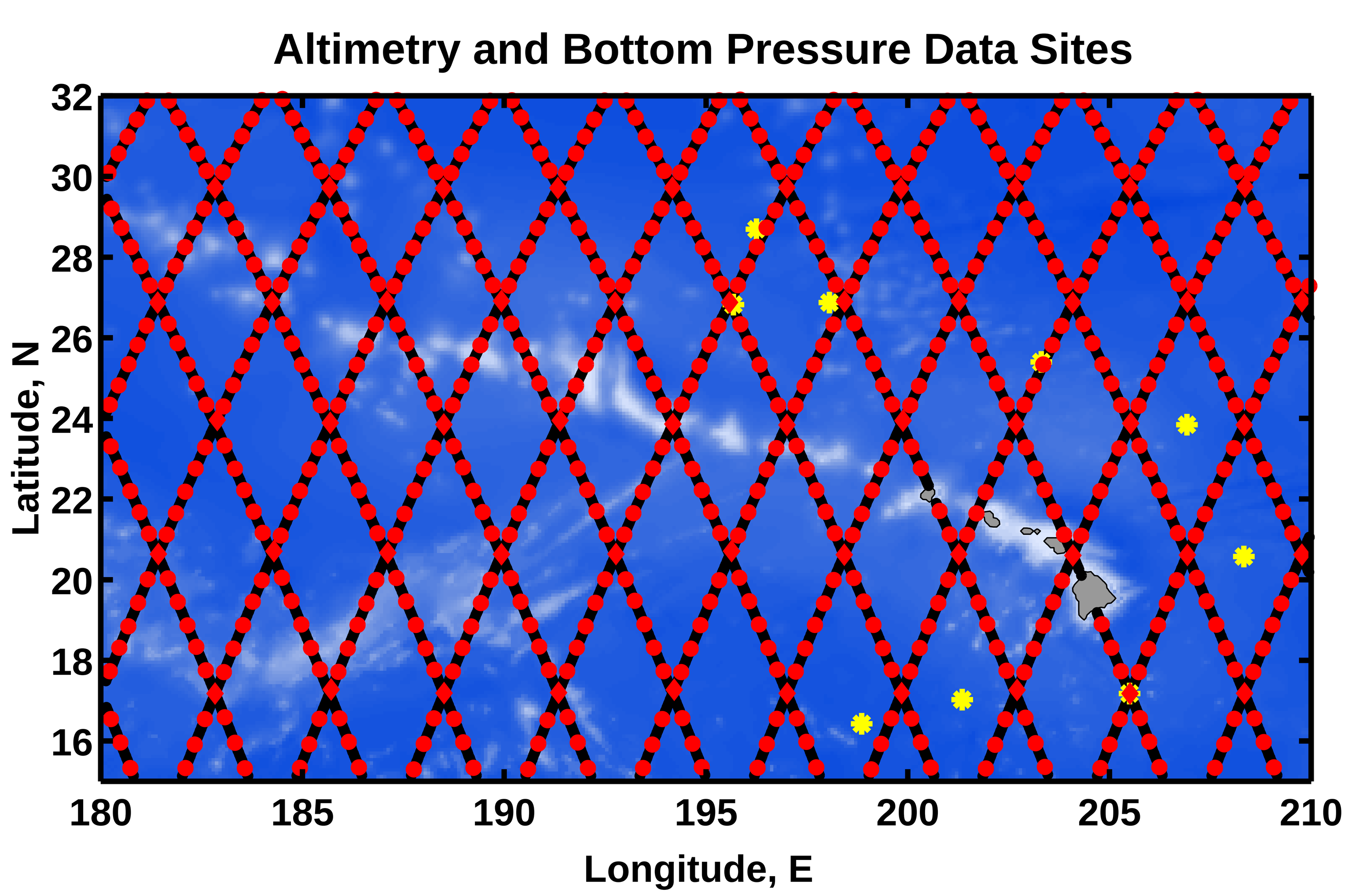
Introduction

- *Baroclinic Conversion* occurs when the barotropic tide flows across bathymetric features, periodically displacing the isopycnals, and generating internal waves.
- *The Baroclinic or Internal Tide* may propagate away from its site of genesis and dissipate via various nonlinear interactions (critical layer processes, elastic scattering, induced diffusion, and parametric subharmonic instability) or via essentially linear boundary reflections.
- The net difference between the baroclinic conversion and radiated internal wave energy is *Energy Available for Mixing*.

The divergence of the barotropic (depth-integrated) energy flux is a source of energy for both internal waves and turbulent mixing near the Hawaiian Ridge. In theory, one can distinguish the linear process of baroclinic conversion from the nonlinear mixing processes. In practice, observational field programs can only sample over a limited domain in space and time, making it difficult to actually distinguish the various processes.

Using a variety of data sources, we are able to estimate the energy lost from the barotropic tide. A portion of this energy radiates away from the Hawaiian Ridge as internal waves, which we are currently studying using ocean models. The remaining energy is available for mixing.

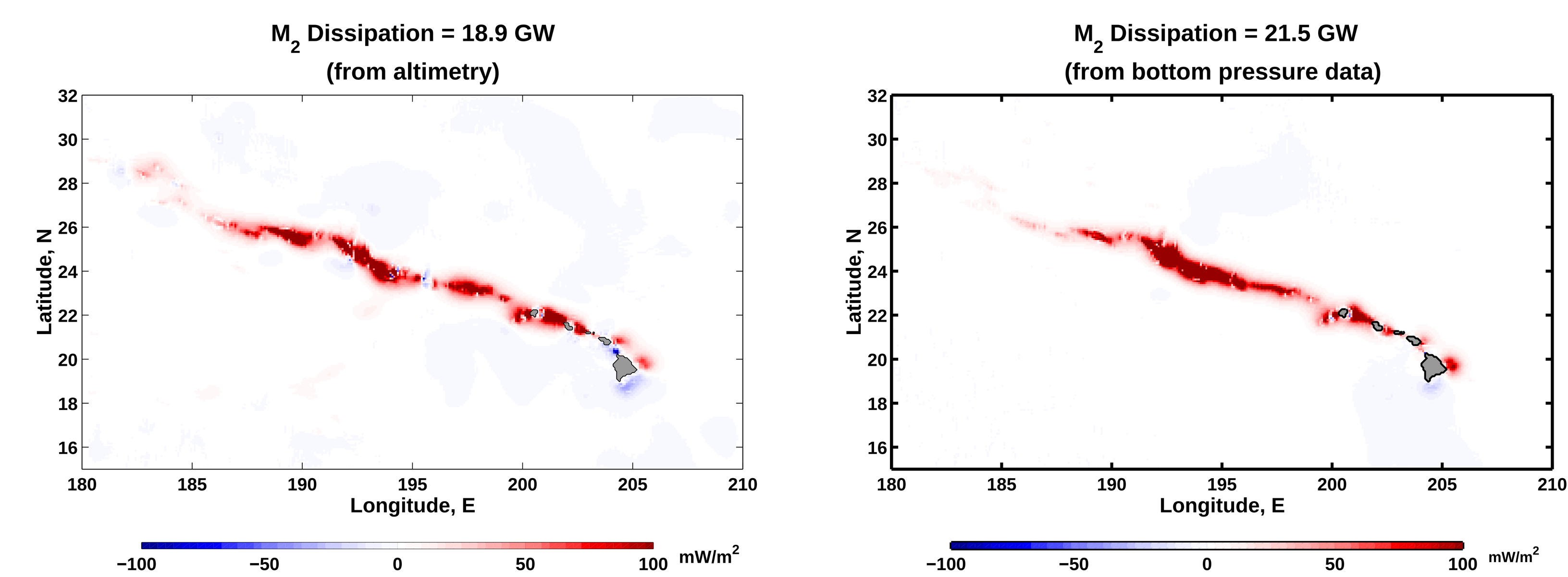
Data: TOPEX/POSEIDON Altimetry and Hawaii Ocean Mixing Experiment (HOME) Bottom Pressure



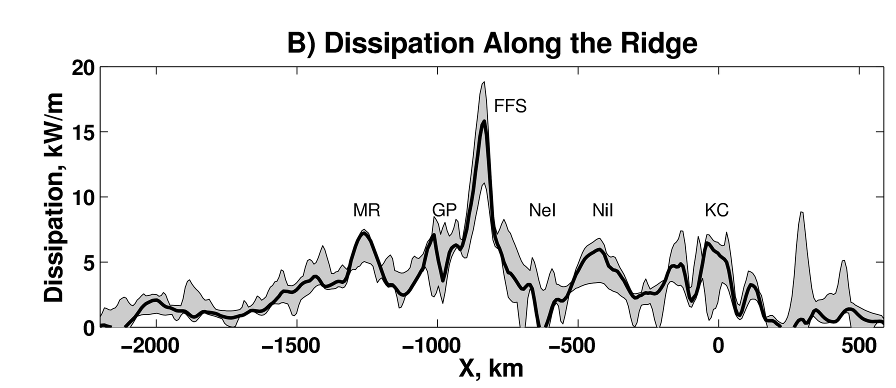
The data assimilation used over 2,000,000 altimeter observations at nearly 8,000 sites (red dots and blue lines). *In Situ* bottom pressure data (yellow stars) were used in a separate calculation to validate the results obtained from the satellite data.

Energy Lost from the Surface Tide

- Generalized inversion of the Laplace Tidal Equations, together with both TOPEX/POSEIDON and *in situ* data, has been used to estimate the barotropic tide in a region surrounding the Hawaiian Ridge.
- The 8 major constituents of the barotropic tide lose approximately $22\mathrm{GW}$ ($1\mathrm{GW} = 10^9$Watt) within 250km of the Hawaiian Ridge.
- There is good agreement between dissipation estimates obtained from satellite altimeter data (TOPEX/POSEIDON) and *in situ* bottom pressure data.



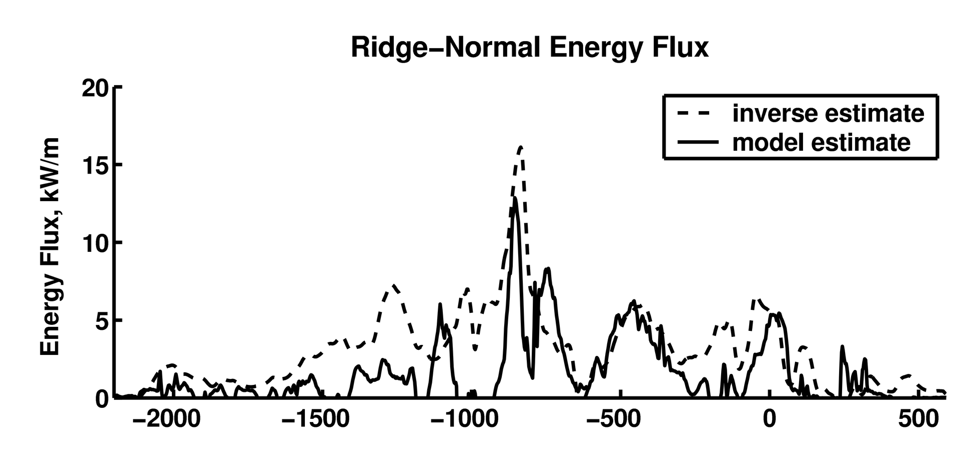
The plots show the barotropic tidal dissipation (i.e., the energy flux convergence of the surface tide) inferred from the altimeter data and the bottom pressure sensors. The agreement between these two estimates is remarkable given the relative paucity of the *in situ* data as compared to the altimeter data.



The plot shows the range of M_2 dissipation estimates which are obtained when the assumptions of the data assimilation are changed. The range of solutions (gray) dissipates between 16 and 22 GW, while our nominal best (solid) estimate dissipates 17 GW within 250km of the Ridge. A lower bound on the dissipation due to all constituents is approximately 20 GW within 250km of the Ridge.

Constituent	Dissipation (GW)	Fraction on Ridge (%)
M_2	19	88
S_2	3.1	91
N_2	0.50	88
K_2	0.33	92
K_1	1.4	85
O_1	0.32	85
P_1	3.0×10^{-2}	98
Q_1	6.1×10^{-3}	10

The table shows the amount of energy lost by each of the 8 consitituents in the model domain. Dissipation at the M_2 and K_1frequencies is most reliably estimated, with an uncertainty of about 10%.

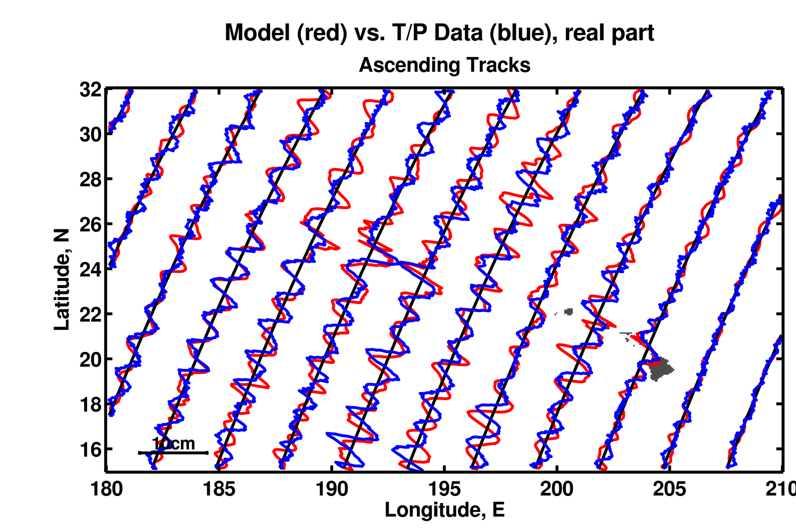


The best estimate of energy lost from the M_2 barotropic tide (computed via generalized inversion of altimetry data) is compared with the the Ridge-normal component of the M_2 baroclinic energy flux computed from PEZ (the ocean model discussed in the next column). The difference between the curves is an initial estimate of M_2 energy available for mixing (8 GW).

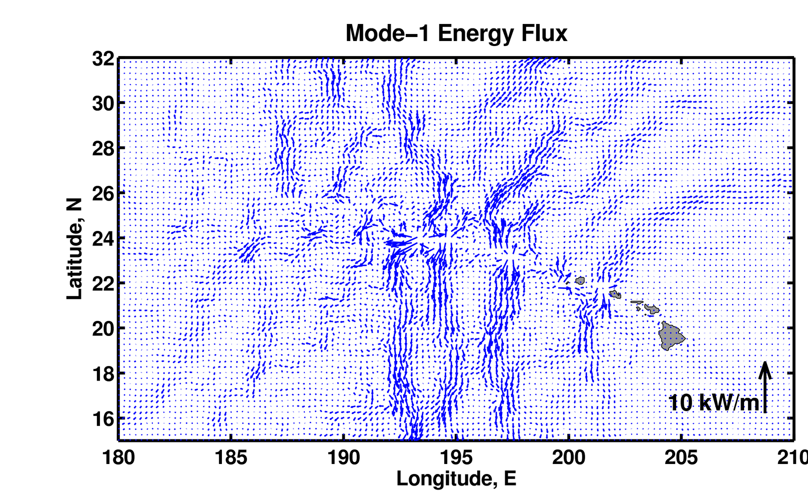
Energy Radiated as Internal Waves

The energy flux of M_2 internal waves has been determined from a primitive equation model.

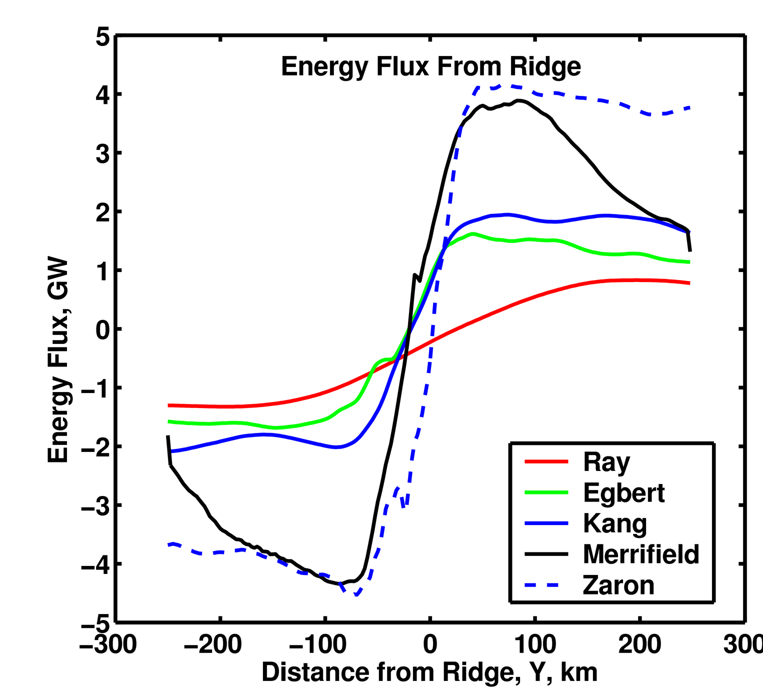
- Primitive Equation Z-Coordinate (PEZ) model: a translation of the Modular Ocean Model 3 for symmetric multiprocessor parallel computers by Bennett and Chua.
- Resolution: $1/16^o$ horizontal, 30 vertical levels logarithmically spaced to resolve the upper ocean.
- Bathymetry: Smith and Sandwell, with the immersed-boundary ghost-cell method of Tseng and Ferziger.



The figures compare the model output with harmonically analysed TOPEX/POSEIDON data. The surface expression of the internal tides is evident in both the model output and the altimeter data. Note the comparable amplitude of the modeled and observed signals.



The energy flux of the first baroclinic mode is shown. A large portion of the energy flux is carried by a few beams which appear to meander from their sites of origin. The first mode is responsible for 7.0 GW of energy transport from the Ridge.



The plot at left shows the Ridge-normal baroclinic energy flux computed from several models (Kang: 2.5-layer reduced gravity; Merrifield and Holloway: $1/24^o$ POM; Zaron: $1/16^o$ PEZ) and data analyses (Ray: T/P local waves; Egbert: T/P reduced gravity).

The Ridge-normal baroclinic energy flux of the three-dimensional modeling studies obtains a peak value which is significantly larger than the peak energy flux based on altimetry data analyses. Our working hypothesis is that the ground tracks of the TOPEX/POSEIDON satellite undersample the beams of propagating baroclinic energy (shown in the panel above).

Summary

Work is ongoing to develop an energetically coherent picture of tidal mixing at the Hawaiian Ridge.

- The M_2 surface tide loses approximately $16.7\mathrm{GW}$ within 250km of the Hawaiian Ridge. Simulations with three-dimensional primitive-equation models indicate that the low-mode internal tide carries roughly $9\mathrm{GW}$ away to the deep ocean. That leaves approximately $8\mathrm{GW}$ available for turbulent mixing at the Ridge, due solely to the M_2 tide.
- The non-M_2 barotropic tide loses approximately $5\mathrm{GW}$ at the Ridge. Experiments are underway to quantify how much of this energy is available for mixing.
- Numerical experiments indicate that much of the internal tidal energy is confined to beams which propagate to the north and south of the Ridge. Work is underway to validate the numerical model and verify the existence of these beams with ERS and GEOSAT altimetry data, which have closer track spacing than the TOPEX/POSEIDON data.
- In the future we will look at how the mesoscale eddy field and background stratification modify the tidal internal wave field. We are also developing the generalized inverse of PEZ for data assimilation studies. Our ultimate goal is to improve our understanding of the role of tides in oceanic mixing.