Internal tides from altimeter

Jinbo Wang

Presented for Patrice's class @ Caltech

5/4/2017

In a discussion of tide-gauge data from Honolulu and La Jolla, MUNK, ZETLER and GROVES (1965) first called attention to the existence of "tidal cusps", a general rise in the oceanic background noise that surrounds the semidiurnal and (sometimes) diurnal tidal bands. The cusp in the semidiurnal band at Honolulu is easily seen in Fig. 1 (lower panel), which is adapted from MUNK and CARTWRIGHT (1966). In this figure, the total column heights give the observed sea-level spectrum at 1 cycle/month resolution, estimated from 20 years of hourly data. The unfilled portion of each column gives the energy at that frequency that is incoherent with the astronomical potential. This incoherent energy is seen to rise at the very low frequencies, reflecting the well-known "redness" of the ocean sea level (similar, of course, to many other geophysical processes), and it also rises noticeably about the semidiurnal tides. (The one column of large noncoherent energy in the diurnal band, evidently at the K_1 tidal group, should be ascribed to radiational forcing associated with S_1 and its seasonal variations.) Between tidal bands, the spectrum is fairly nondescript (MUNK and BULLARD, 1963). A tidal cusp surrounding the semidiurnal band turns out to be a common feature of sea-level spectra; a cusp around the diurnal band is less common but can still be seen in some locations.

MUNK *et al.* (1965) suggested that tidal cusps are due to nonlinear interactions between tidal spectral lines and the intense low-frequency continuum. Much like the familiar shallow-water interaction between two tides, which causes secondary signals at summed and differenced frequencies, nonlinearity with the continuum would act to smear tidal lines, hence generating the cusp-like spectral shape. Munk *et al.* added that "it is amusing to contemplate that a record of the climatic fluctuation is contained in the cusps and could in principle be recovered by demodulation at tidal frequencies. Thus one could study the low-frequency fluctuations even if the recording instruments do not have the prerequisite long-term stability".

The next year MUNK and CARTWRIGHT (1966) reexamined this theory of tidal cusps and rejected it. Using data from Honolulu and Newlyn (England), they computed the relevant bilinear coherences for the noise-line interaction and they found them insignificant. They then considered three further hypotheses: (1) that the cusps were merely due to numerical defects in computing the spectra, (2) that the cusps were due to nonlinearity in the tide gauges (including, for example, octopus tentacles in orifices) and (3) that the cusps were due to nonlinear interaction with a distant, rather than local, low-frequency continuum. All three hypotheses were rejected. In the end they concluded "we have no convincing model". But they then added:

> Toshitsugu Sakou and Gordon Groves (personal communication) have made the interesting suggestion that the cusp energy represents the small surface oscillations associated with internal tides. The

Surface manifestation of internal tides in the deep ocean: observations from altimetry and island gauges[1]

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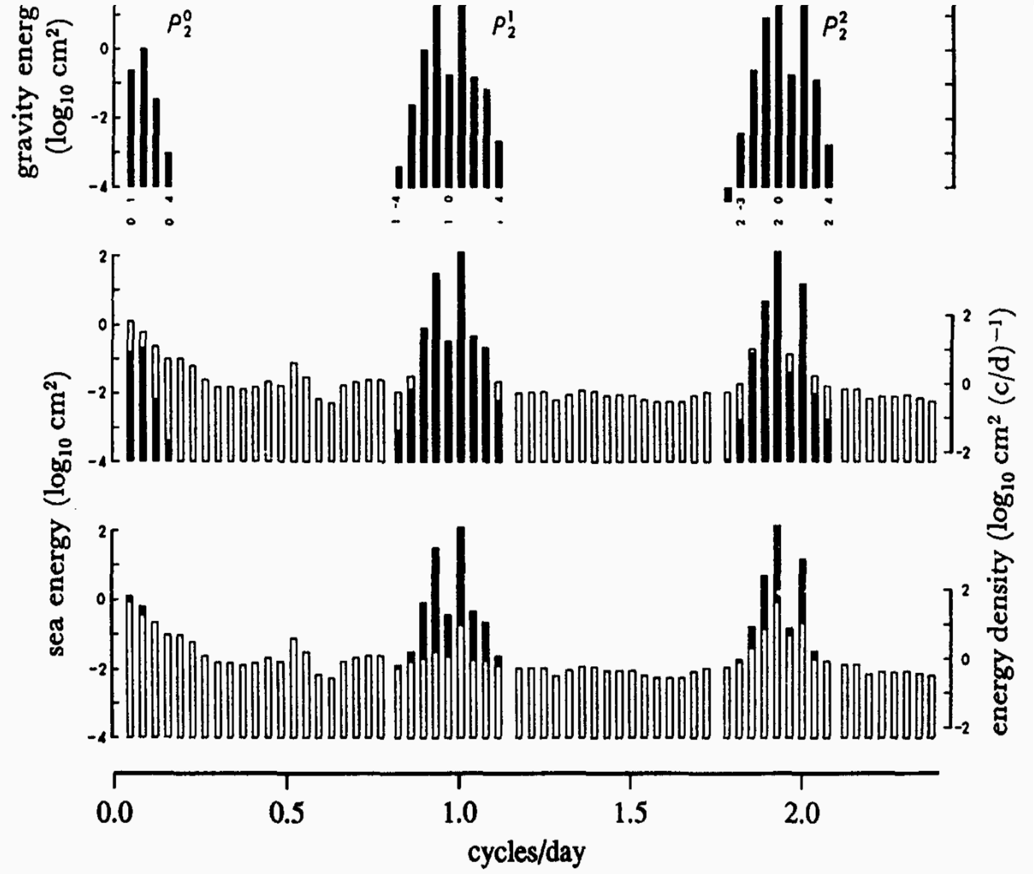

Fig. 1. Honolulu sea level spectrum at 1 cycle/month resolution, according to MUNK and CARTWRIGHT (1966). The upper panel shows the energy of the gravitational equilibrium tide at Honolulu; the lower two panels show the observed sea level spectrum. In the middle panel, the height of the filled portion of each column denotes the energy that is coherent with the astronomical potential; in the lower panel, the height of the unfilled portion denotes the energy that is incoherent. (Two panels are required because of the logarithmic scale.) The left axis gives energy in each column; the right axis gives energy per cycle/day. Reproduced by permission of the Royal Society.

In a discussion of tide-gauge data from Honolulu and La Jolla, MUNK, ZETLER and GROVES (1965) first called attention to the existence of "tidal cusps", a general rise in the oceanic background noise that surrounds the semidiurnal and (sometimes) diurnal tidal bands. The cusp in the semidiurnal band at Honolulu is easily seen in Fig. 1 (lower panel), which is adapted from MUNK and CARTWRIGHT (1966). In this figure, the total column heights give the observed sea-level spectrum at 1 cycle/month resolution, estimated from 20 years of hourly data. The unfilled portion of each column gives the energy at that frequency that is incoherent with the astronomical potential. This incoherent energy is seen to rise at the very low frequencies, reflecting the well-known "redness" of the ocean sea level (similar, of course, to many other geophysical processes), and it also rises noticeably about the semidiurnal tides. (The one column of large noncoherent energy in the diurnal band, evidently at the K_1 tidal group, should be ascribed to radiational forcing associated with S_1 and its seasonal variations.) Between tidal bands, the spectrum is fairly nondescript (MUNK and BULLARD, 1963). A tidal cusp surrounding the semidiurnal band turns out to be a common feature of sea-level spectra; a cusp around the diurnal band is less common but can still be seen in some locations.

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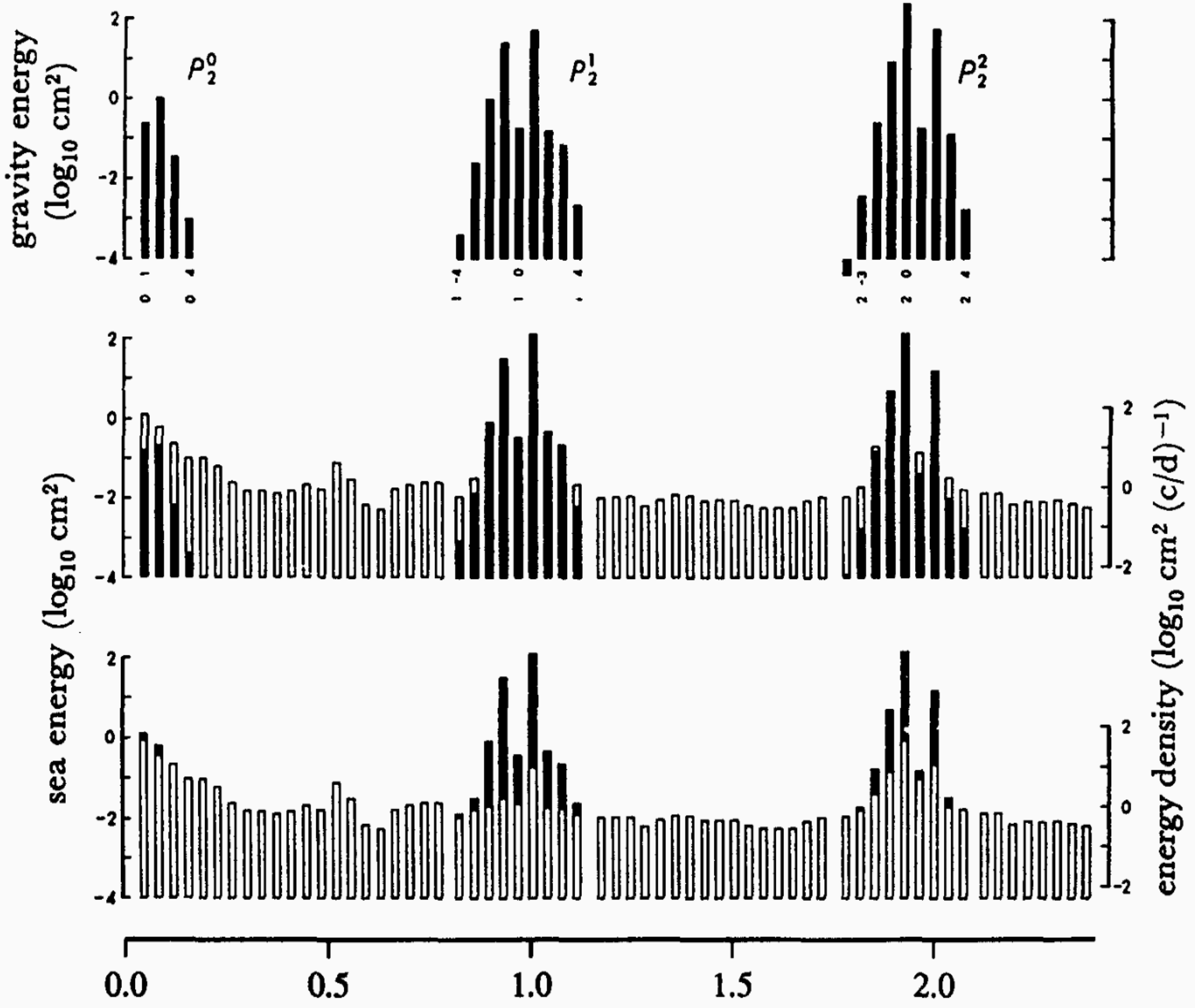

Toshitsugu Sakou and Gordon Groves (personal communication) have made the interesting suggestion that the cusp energy represents the small surface oscillations associated with internal tides. The spreading into cusps is to be associated with a modulation of the internal tides by the slowly varying thermal structure (MUNK and CARTWRIGHT, 1966).

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Time domain
Harmonic analysis

$$\eta(t) = a\cos(\omega_0 t - \phi)$$

New Altimetric Estimates of Mode-1 M_2 Internal Tides in the Central North Pacific Ocean

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(Manuscript received 26 September 2007, in final form 21 January 2009)

ABSTRACT

1. Barotropic tides can be removed by spatial filtering or tidal models like GOT99
2. After correction, SSH is fitted to the sinusoidal model to estimate a and ϕ

$$\eta(t) = a\cos(\omega_0 t - \phi)$$

Zhao and Alford, 2009

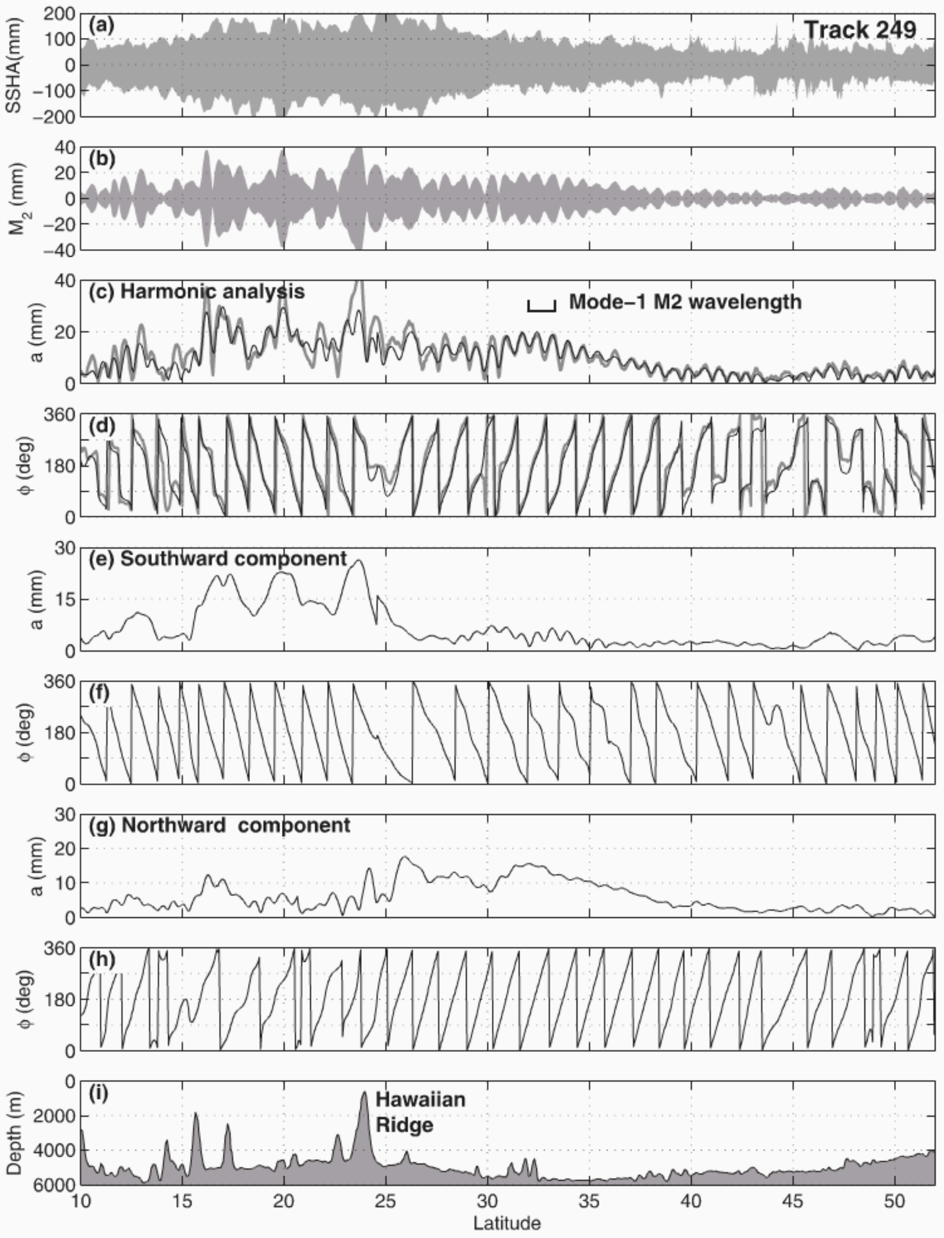

FIG. 3. Altimetric signals along T/P track 249: (a) raw sea surface height anomaly (SSHA) in all cycles; (b) the M_2 SSHA extracted by harmonic analysis; (c),(d) the M_2 amplitude and phase obtained by harmonic analysis (gray) and by superposing the southward and northward components (black); (e),(f) the M_2 amplitude and phase of the southward component; (g),(h) the M_2 amplitude and phase of the northward component. (i) Along-track bottom topographic profile. The theoretical along-track wavelength for a mode-1 M_2 internal tide (~160 km) is indicated in (c).

Plane wave fitting

$$\eta = a\cos(k_0 x \cos\theta + k_0 y \sin\theta - \omega_0 t - \phi),$$

Zhao and Alford, 2009

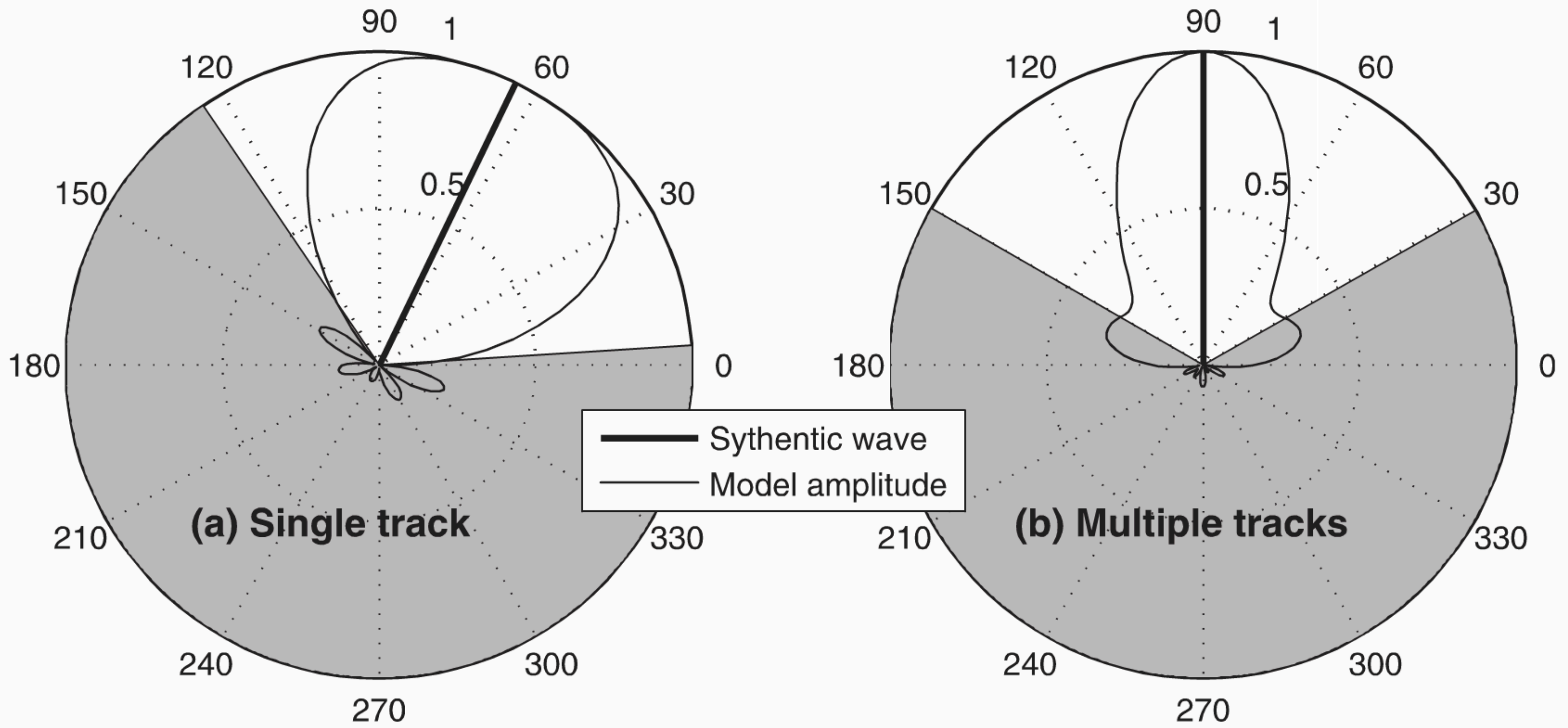

FIG. 6. (a) Model amplitude computed for each direction from data along a single track (see section 3c) for a synthetic wave of unit amplitude traveling along the track (heavy black). (b) Plane-wave model amplitude computed from multiple tracks for each direction (see section 3d) for a synthetic wave traveling toward the north (heavy black). In the gray regions, the model amplitude rapidly attenuates because of the mismatch between the actual and assumed directions.

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2014JC010014

Internal tide radiation from the Luzon Strait

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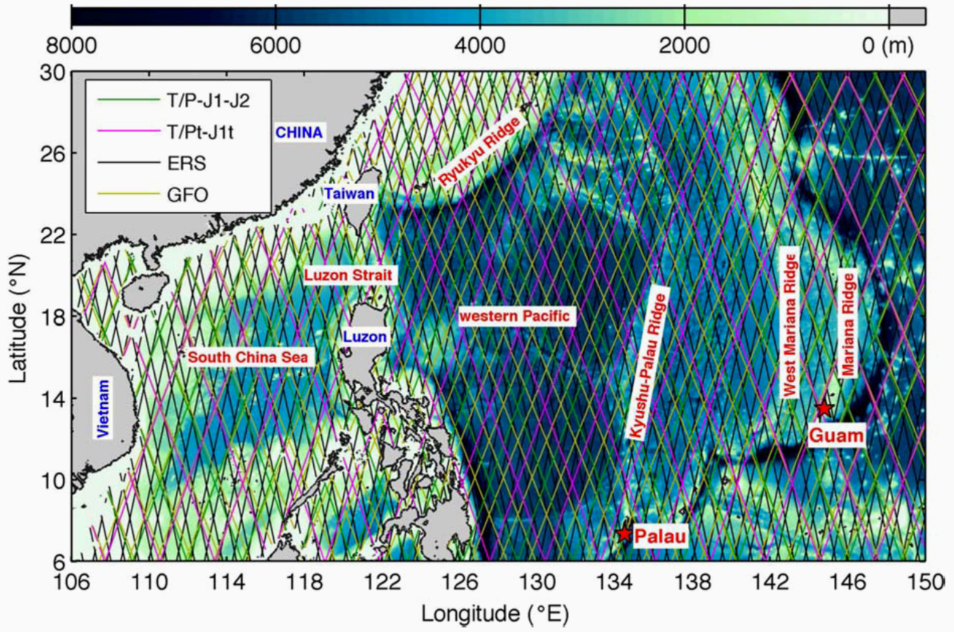
Key Points:

- Luzon Strait radiates internal tides



Plane wave fitting

$$\eta(a, \phi, \theta) = a\cos(k_0 x \cos\theta + k_0 y \sin\theta - \omega_0 t - \phi),$$

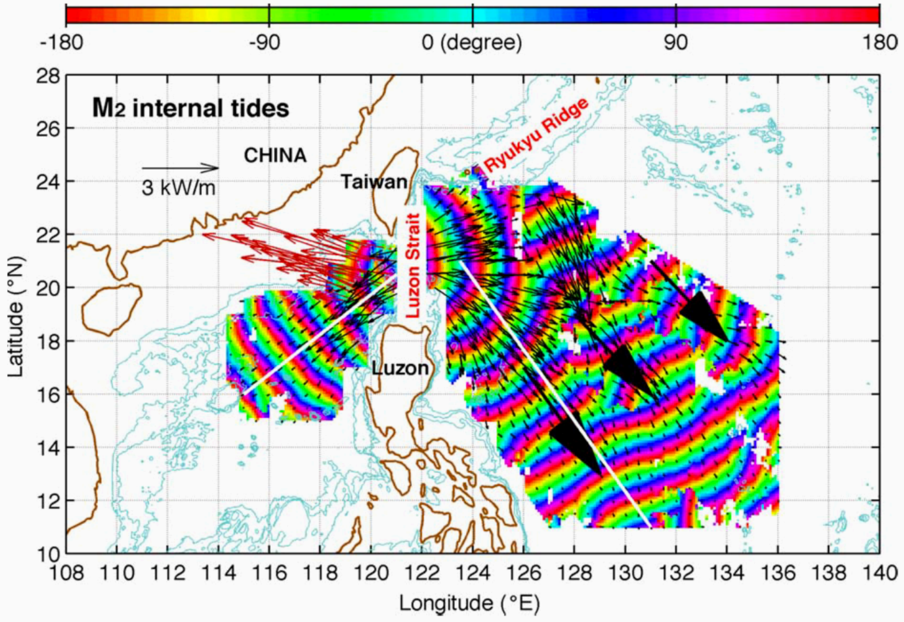


Figure 6. As in Figure 4 but for the mode-1 M_2 internal tides. There are two beams in the SCS. The red arrows show the energy fluxes of the northwestward beam. The bold arrows indicate three distinct beams formed by the internal tides from the Luzon Strait and the Ryukyu Ridge. The white curves indicate the central paths of two M_2 beams.

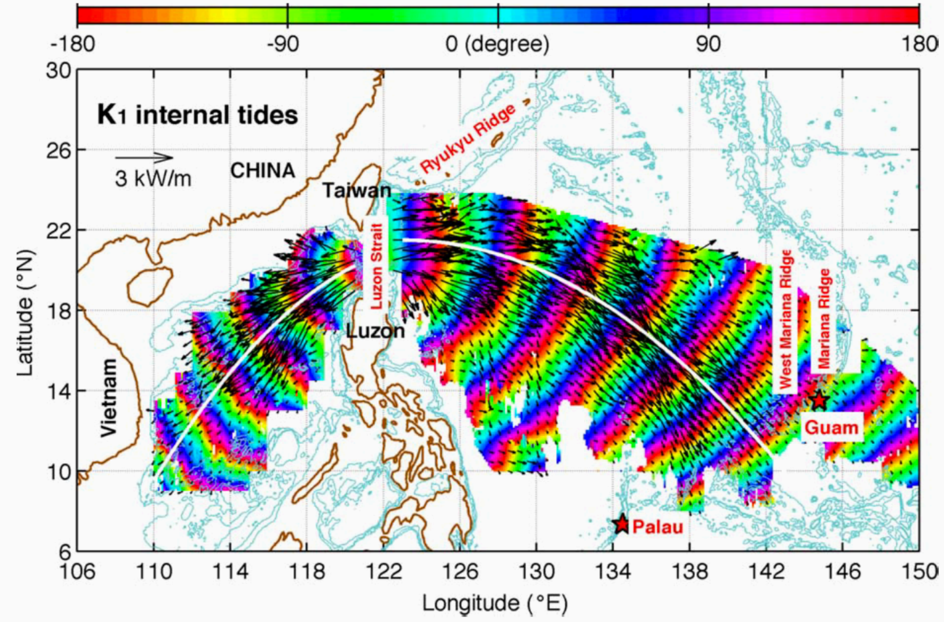


Figure 4. The mode-1 K_1 internal tides from the Luzon Strait. The colors indicate the Greenwich phase. The arrows indicate the depth-integrated energy flux. The 1000, 2000, and 3000 m isobaths are shown in light cyan. The white curves indicate the central paths of two K_1 internal tidal beams.

Non-stationary internal tides observed with satellite altimetry

R. D. Ray[1] and E. D. Zaron[2]

Received 21 June 2011; revised 11 August 2011; accepted 12 August 2011; published 9 September 2011.

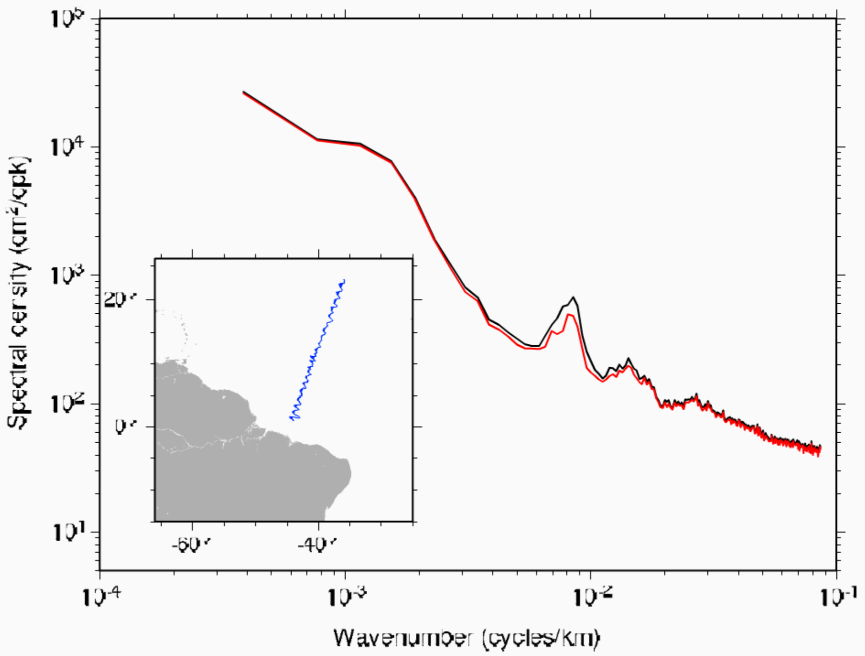


Figure 5. As in Figure 4 but for a track off the Amazon Delta extending into the Atlantic. For this track the internal-tide peaks appear mostly non-stationary.

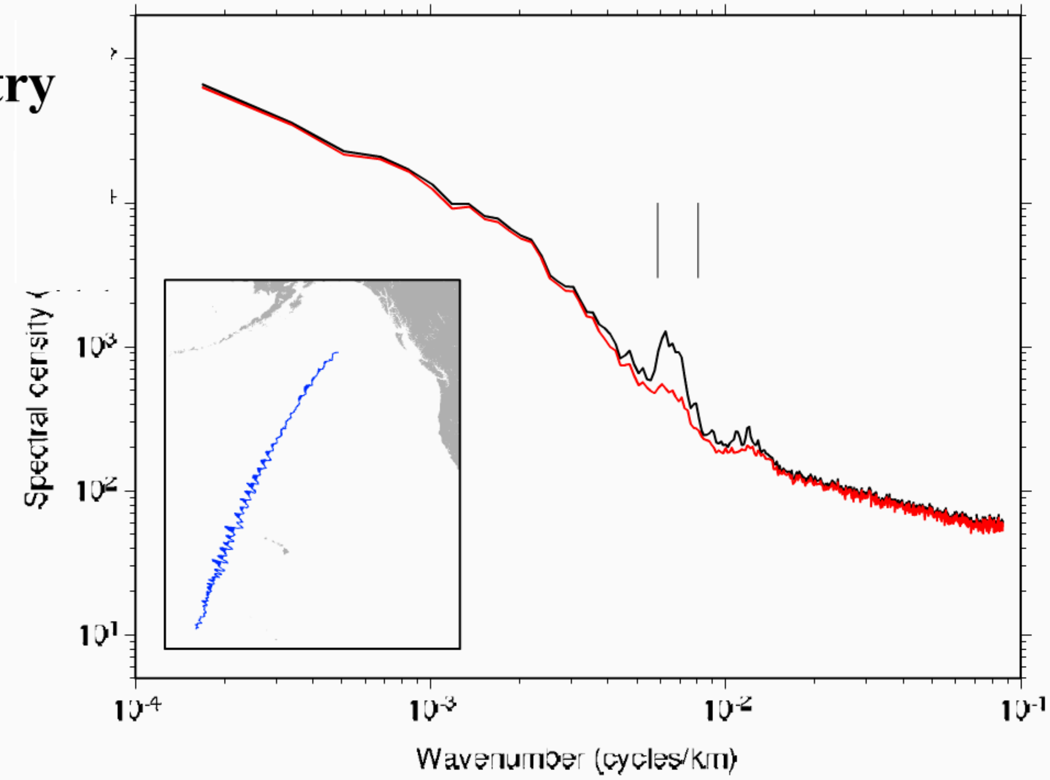


Figure 4. Along-Track Wavenumber Spectrum. Black curve shows the 17-year average wavenumber spectrum of SSH on a ground track through the central North Pacific, where the internal tide signal is large. Barotropic tides were removed via model GOT4.7. Red curve shows the same spectrum after estimating and removing residual tides (relative to model), point by point along the track. Vertical lines denote the expected wavenumber range of mode-1 semidiurnal internal waves along this track. The de-tided spectrum still contains elevated variance at both the first- and second-mode wavenumbers, which is attributed to the non-stationary internal tide.

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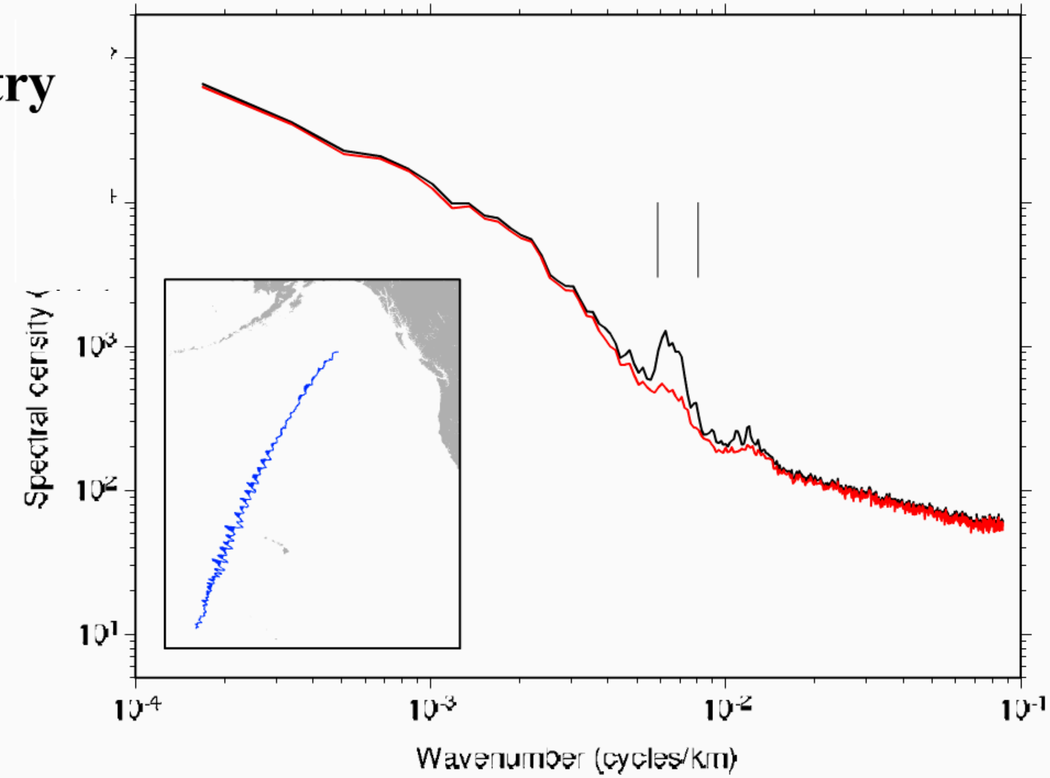
[1] Temporal variability of the internal tide is inferred from a 17-year combined record of Topex/Poseidon and Jason satellite altimeters. A global sampling of along-track sea-surface height wavenumber spectra finds that non-stationary variance is generally 25% or less of the average variance at wavenumbers characteristic of mode-1 tidal internal waves. With some exceptions the non-stationary variance does not exceed 0.25 cm^2. The mode-2 signal, where detectable, contains a larger fraction of non-stationary variance, typically 50% or more. Temporal subsetting of the data reveals interannual variability barely significant compared with tidal estimation error from 3-year records. Comparison of summer vs. winter conditions shows only one region of noteworthy seasonal changes, the northern South China Sea. Implications for the anticipated SWOT altimeter mission are briefly discussed.

Citation: Ray, R. D., and E. D. Zaron (2011), Non-stationary internal tides observed with satellite altimetry, *Geophys. Res. Lett.*, *38*, L17609, doi:10.1029/2011GL048617.



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