Non-Stationary Internal Tides Observed with Satellite Altimetry

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Non-stationary internal tides observed with satellite altimetry

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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.


1. Introduction

[2] In situ measurements of internal tides are typically characterized by high temporal variability, with strong dependence on stratification, mesoscale eddies, and background currents. For example, analysis of open-ocean current-meter records often finds little coherence of the signal near tidal frequencies [Magaard and McKee, 1973; Weisberg et al., 1987], and low coherence has also been observed in open-ocean temperature measurements [Barnett and Bernstein, 1975].

[3] There are, however, exceptions to this picture. Some observations suggest phase locking to the spring-neap cycle [Siedler and Paul, 1991]. Moreover, near presumed generation sites such as submarine ridges, baroclinic tidal currents can be phase-locked to barotropic tides [Chiswell, 2000]. For example, the partial coherence of the internal tide observed during the MODE experiment has been partly explained by the proximity to the presumed generation site [Hendry, 1977].

[4] The detection of internal tides in sea-surface height (SSH) by satellite altimetry—at least in the manner it is usually done [Ray and Mitchum, 1996]—in fact relies on having a signal phase-locked (stationary) over a period of years. So the question naturally arises: How much tidal variability is missed by altimetry? The practical significance of this question is related to the anticipated SWOT wide-swath altimeter mission, for which removal of internal tide signals is critical for observing non-tidal submesoscale phenomena [Fu and Ferrari, 2008; Chavanne and Klein, 2010]. In addition, satellite altimeters are one of the few sources of data available to calibrate and validate high-resolution numerical models which are now incorporating tides on a global scale [Arbic et al., 2010].

[5] To some extent the altimetric picture of internal tides is necessarily simpler and more stationary than the one suggested by in situ measurements because SSH acts as a “high-mode filter.” For example, in a constant-buoyancy ocean the vertical displacement of each baroclinic mode $n$ is reduced at the surface by a factor $n^{-1}$ [Hendershott, 1981, equation (10.40)]. Higher modes, which are more sensitive to changes in the ocean medium, are suppressed in altimeter data. Yet even in the dominant low modes some variability must surely remain.

[6] Our approach to identifying tidal variability proceeds along two lines. First, seasonal and interannual variability of the internal tide is examined by performing tidal analyses of the altimeter data over selected time periods and subsets. Over most of the ocean changes are remarkably small, except in the South China Sea which is examined in some detail. The second approach relies on an analysis of along-track SSH wavenumber spectra. Mode-1 and mode-2 internal tidal SSH variance tends to concentrate within a fairly small band of wavenumbers, and the energy in these bands may be compared against the non-tidal background spectrum to infer the variance in the stationary and non-stationary tide.

2. Time-Domain Analysis

[7] The time series from the Topex/Poseidon and Jason (T/P-J) satellites is sufficiently long that tides may be reliably estimated from independent subsets of the data. Such independent estimates, each based on 3 to 5 years of data, shed light on potential interannual variability in the signals.

[8] Figure 1 illustrates the variations of the major semidiurnal tide ($M_2$) from temporal subsets of T/P-J data near the Hawaiian Ridge. The complex harmonic constants have been determined by a response-type tidal analysis independently for each point along the satellite ground track. A model (GOT4.7) of the barotropic tides (plus solid-earth tides) was applied before tidal analysis. We also removed much of the non-tidal variability by using weekly multi-mission altimetric SSH gridded data as a prior correction to our along-track data [Ray and Byrne, 2010]. Estimated tides were subsequently high-pass filtered (approximate wavelength cutoff of 400 km) to further emphasize the internal tide signal. The sinusoidal variations with wavelength near 150 km are attributed to the first-mode internal waves, which propagate with an approximate phase speed of 2.9 m s$^{-1}$ [Chiswell, 2002].

[9] Careful examination of Figure 1 does reveal small changes from one period to the next. For example, the
Figure 1. $M_2$ in-phase and quadrature components (the latter offset by 5 cm) deduced from T/P-J altimetry along a single track crossing the Hawaiian Ridge. Heavier black lines are computed from nearly all available altimeter passes. Four light lines are computed after partitioning the data into independent 3-year subsets. Largest differences are seen in the orange curve, for data from 1996–1999. Note that the surface tide has been removed from the data. Bottom panel shows the bottom topography under the satellite ground track.

in-phase anomaly between 25°–26°N disappeared during one period. But overall the consistency among the different periods is very high. Mean-square differences between the 17-year average and the 3-year subsets range from 0.22 cm$^2$ to 0.39 cm$^2$, approximately 0.14 cm$^2$ of which can be attributed to estimation error in the harmonic constants, primarily in the 3-year solutions.

Data have also been analyzed in November–March (winter) vs. June–September (summer) subsets. Figure 2 shows high-passed along-track data for the North Pacific. One sees that the winter and summer data closely overlap, allowing for small random measurement error. Similar results may be seen globally, with few exceptions, one of which is seen in Figure 3. Along one track west of the Philippines in the South China Sea there is a significant phase offset in the $M_2$ internal tide (which in that region propagates from the Luzon Strait). In one section the seasonal estimates are almost completely out of phase. This phase offset is consistent with seasonal variations in upper ocean stratification and subsequent modification of the mode-1 internal wave phase speed in this region [Zhao and Alford, 2006; Jan et al., 2008]. We return to the South China Sea example below.

Thus, in contrast to in situ measurements, the internal tide observed by the T/P-J altimeters is remarkably stationary. At very few sites is there marked seasonal variability, and a global survey (not shown) has noted no sites with substantial interannual variability. There are several caveats to this analysis. First, the analysis has still relied on recovery of a phase-locked signal, be it over 3–4 years or by season. Second, the internal tide is less reliably extracted in western boundary currents or other regions with large eddy kinetic energy, even using the ‘trick’ of Ray and Byrne [2010]; in these regions non-tidal variance at the tidal alias frequencies makes tidal estimation less accurate, especially so for diurnal tides.

3. Wavenumber-Domain Analysis

The presence of an internal tide signal is evident in Figures 1 and 2 precisely because the signal is spatially...
coherent and nearly sinusoidal on the scale of the mode-1 internal tide wavelength. Here we use variance in the mode-1 and mode-2 wavenumber-bands to examine temporal coherence and stationarity. Unlike the previous section, prior corrections for non-tidal variability are not applied, aside from a standard adjustment for atmospheric loading.

Figure 4 shows the along-track wavenumber spectrum computed from 17 years of T/P-J data on a ground track in the North Pacific, passing near French Frigate Shoals, a significant site of internal tide generation on the Hawaiian Ridge. The spectrum has been computed by averaging the periodograms obtained from 495 repeat cycles. The overall shape of the spectrum is red, with form similar to what has been documented previously [Fu, 1983; Stammer, 1997]. There are, however, noticeable elevations in energy near the expected mode-1 and mode-2 semidiurnal internal-tide wavelengths. Rather than being concentrated at a single wavenumber, this energy is spread over a range of wavenumbers for several reasons: (1) the ground track is in general not parallel to the wavenumber of the internal waves (cf., internal tide beams and their spatial variability as shown by Merrifield et al. [2001] and Simmons et al. [2004]), (2) the wavenumber of propagating internal waves is a function of both the Coriolis parameter and stratification, which vary spatially along the track, (3) the wavenumber depends on tidal frequency, which varies by 8% across the semidiurnal band; and (4) evanescent or topographically trapped waves may be present. For the ground track segment pictured, the expected variations in the Coriolis parameter is about a factor of 1.5. Analysis of shorter ground track segments is a trade-off between wavenumber resolution vs. bandwidth spreading due to the above-mentioned factors.

The red curve in Figure 4 was computed the same way except that, prior to computing the periodograms, a harmonic

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.
tidal analysis for 12 major constituents was performed point-by-point along the track and used to remove any residual tide. Variance within the mode-1 band is considerably reduced although not completely eliminated. We attribute this residual hump to non-stationary tidal energy over the 17-year record. The variance in the mode-2 band is comparatively more non-stationary. Based on a (slightly subjective) determination of the background spectrum, we estimate the variance in the two modal bands as 1.19 cm² and 0.26 cm² before de-tiding and 0.23 cm² and 0.12 cm² after.

Space precludes presenting a thorough review of global ocean spectra of this type. At many sites there is hardly any evidence of a peak in the expected modal bands. At other sites the mode-1 peak is nearly totally stationary and is almost wholly removed by along-track tidal analysis. Figure 5 shows a case of opposite extreme, for which the peaks are fairly large and a large non-stationary part remains. The variance in the mode-1 band is 1.07 cm² and 0.46 cm², before and after de-tiding. The mode-2 band is almost wholly non-stationary. There is a suggestion of another small peak at higher wavenumbers, which de-tiding does nothing to eliminate. The 0.46 cm² residual is the largest we have so far observed; most are less than half that.

The South China Sea track discussed in Section 2 has a most interesting spectrum, shown in Figure 6. For this case the de-tiding has been done in steps: diurnal constituents only, then diurnal plus semi-diurnal, then diurnal plus semi-diurnal with seasonal (annual and semi-annual) modulations. Figure 6 is noteworthy for several reasons. First, it shows one of the clearest examples in altimeter data anywhere for a diurnal internal tide, with wavelength roughly 300 km. Although it is difficult to establish the background spectrum unequivocally, the variance in the diurnal band appears to be roughly 3 cm², most of which is removed by de-tiding. Figure 6 also shows the presence (because of the gap between red and orange curves) of a diurnal mode-2 wave that overlaps the semi-diurnal mode-1. Finally, the lowest (cyan) curve shows that explicitly solving for and removing seasonal modulations of major constituents further reduces the variance, leaving a residual of about 0.19 cm².

As with the previous section, a caveat is required. Our internal-tide variances could be seriously underestimated if energy is not confined to narrow wavenumber bands but is instead spread out across the spectrum. Spreading into lower wavenumbers could occur if an internal wave propagates nearly orthogonal to the satellite track. This seems unlikely given the presence of such obvious peaks at the expected wavenumbers. In fact, long-crested plane waves appear to be rare at the scales we are discussing [Merrifield et al., 2001].

4. Discussion

In contrast to in situ measurements, the majority of internal tidal energy in altimetry is found to be stationary. We attribute this contrast to the selectivity of the altimeter data which predominantly detects just the barotropic (surface) and first baroclinic (internal) mode. It is the higher order modes which are expected to be more strongly influenced by variations in background currents and stratification.

The magnitude of the non-stationary tide as detected by altimetry may be compared with that detected by other measurements of mode-1 internal-tide variability. Dushaw et al. [1995] analyzed a 120-day record of reciprocal acoustic travel time measurements in the central North Pacific. The averaging properties of the acoustic ray paths are highly selective of mode-1 variability. It was estimated that about 15% of mode-1 M₂ tidal variance is due to non-phased-locked tidal variability. Chiswell [2002] analyzed approximately 5 years of inverted echosounder data from station Aloha, 100 km from an internal-tide generation site on the Hawaiian Ridge. He found large (50%) changes in the amplitude of the internal tide; the standard deviation, however, amounts to only about 20% of the mean internal tide (based on Figure 7 of Chiswell [2002]).

Our wavenumber results suggest that the non-stationary variance associated with internal tides is generally well below 1 cm². Analyses of coastal tide-gauge data appear to yield rather different estimates, based on the spectral ‘cusp’ surrounding major constituents. For example, Colosi and Munk [2006] find 1.77 cm² at Honolulu, but a lower 0.65 cm² at Hilo (still larger than our altimetric estimates). The increased variability at Honolulu may stem in part from the larger currents and changes in stratification near the coast, which would be more coupled to the internal tide owing to the lower propagation speed of the latter in shallow water [Alford et al., 2006]. Other near-coastal processes may be at play as well; no one, for example, is likely to attribute the 70 cm² cusp at Liverpool [Cartwright and Amin, 1986] to internal tides. On the other hand, the variability of M₂ at Hilo is known to be similar to that in deep water, at least for periods longer than a few months [Mitchum and Chiswell, 2000].

Even variability of 0.5 cm² as in Figure 5 has important implications for the anticipated SWOT mission. At sites where the mesoscale and sub-mesoscale energy follows a steeply-sloped \( k^{-5} \) (quasi-geostrophic) or \( k^{-11/3} \) (surface quasi-geostrophic) form [LeTraon et al., 2008], much of the signal could be masked by the non-stationary internal tide at wavelengths between 120 km and 180 km.
We stress that Figure 5 is the worst case we have so far encountered, but a more thorough global analysis of wavenumber-implied variability is warranted.

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