EVALUATING UNCERTAINTIES AND MULTI-WAVE INTERFERENCE PATTERNS IN INTERNAL TIDES OBSERVED BY SATELLITE ALTIMETRY

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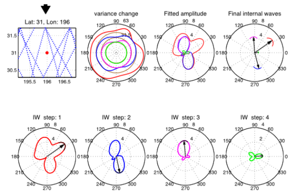
Abstract

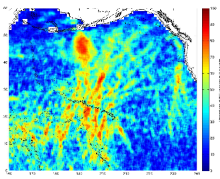
Internal tides (internal waves generated by tidal flow over steep topography seen radiating across ocean basins) have been observed in great detail by fitting low-mode plane waves to multi-altimeter datasets in small sliding sub-regions. This technique is able to identify multiple waves in a given location, but connecting the waves to generation sites requires a certain amount of subjective interpretation. In addition, the surface height signal of the internal tide is typically one to two orders of magnitude smaller than that due to mesoscale eddies, presenting a need to evaluate the the statistical significance of the wave-fitting results in a low signal-to-noise ratio environment.

We explore methods for grouping internal tide waves into coherent beams and connecting these to topographic generation sites. In order to do this, we have also developed complementary methods for evaluating the uncertainty in satellite-derived internal tide amplitude and direction and shown that low-mode internal tides are separable from noise over most of the ocean. The regions of significance diminish in size for the lower-amplitude tidal constituents and for higher vertical mode numbers.

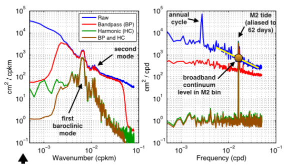
Plane-Wave Fitting and Error Estimation

- Propagating waves of known wavelength (first baroclinic mode) and frequency (M2 tide) are fit to all available satellite sea-surface height (SSH) measurements within a 160 km window (slid by 0.1° increments).
- The best-fit, largest amplitude wave (amplitude, direction, and phase—red arc, upper right panel below) is removed, and the process is repeated. The global M2 mode-1 internal tide dataset shown on this poster is made up of the largest 3 waves (red, blue, magenta) at each location.

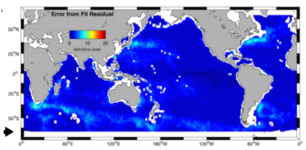




The percentage of M2-frequency variance accounted for by the 3 waves in a region of the North Pacific.



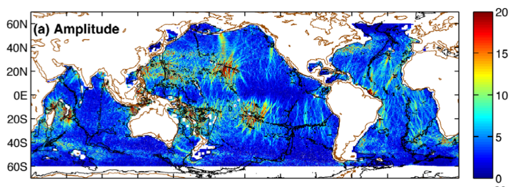
(above) Wavenumber and frequency spectra for a TOPEX/Poseidon track. Internal tides have a known wavenumber-frequency structure, but exist on the shoulder of a large mesoscale spectral slope.



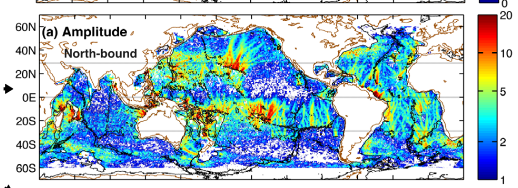
(right) Errors estimated from the residual variance method (Eq. 1 below). Here the number of degrees of freedom (N) has been tuned to match the levels of the eddy-rich regions in the wave amplitude plots below.

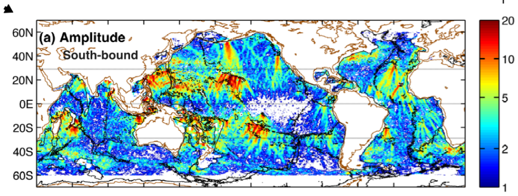
Signal: Long-range Internal Tide Propagation

(right) SSH amplitude of the superposition of all 3 fitted plane waves, illustrating the complex interference patterns that are typical of much of the world's oceans.



(right) Amplitude of the largest northbound (upper) and southbound (lower) plane waves. Phase is shown in the panel to the lower right.





Standard error in a harmonic fit parameter scales as

$$\sigma_A = \frac{\sigma_r}{\sqrt{N}} \qquad (1)$$

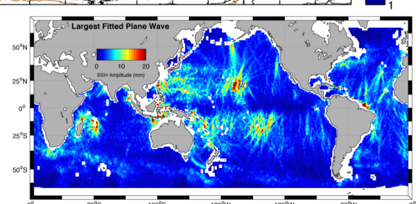
(similar to the standard error in the mean), where σ_r is the residual variance after removing the fit and *N* is the number of degrees of freedom (independent random process realizations which tend to cancel out). A typical tidal analysis technique is to use the broadband spectrum to estimate the noise present in the Fourier bin of the desired constituent (Pawlowicz et al 2002). Then the error is

$$\sigma_A = \sqrt{P \Delta f} \qquad (2)$$

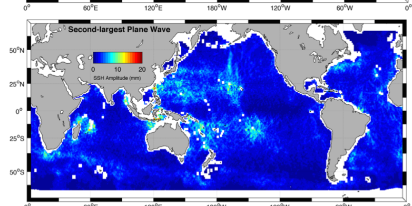
where P is the spectral level of the noise at the harmonic frequency—determined from a linear fit as shown **above**. *Errors* due to broadband noise are shown to the **right** for each satellite track and sampling pattern. Sampling pattern influences the tidal aliasing frequency and spectral resolution.

Degrees of freedom (*N*) are mainly the number of altimeter passes (points in the timeseries). The spatial fitting may provide a few (~5) more, but the 160 km window size is not very effective at removing mesoscale eddies—the dominant noise process here.

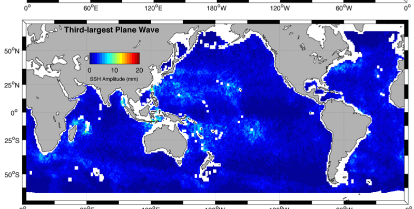
(right) Amplitudes of the first, second, and third fitted waves plotted separately to illustrate their relationship to noise. The smaller amplitude waves are just above the noise floor in many locations of the ocean, but coherent features still persist and play important roles in interference patterns.



It seems fairly clear that the wave fitting is unable to detect internal tide signals in the highly variable regions immediately surrounding each of the western boundary currents (see M2 error maps and the residual error map at the upper right of the poster). However, the fact that these regions can be clearly identified by the methods presented here allows us to make interpretations of internal tide analyses in all other regions with all the more confidence. In addition, we plan to lessen the mesoscale contamination by using eddy-resolving maps as suggested by Ray and Byrne (2010).

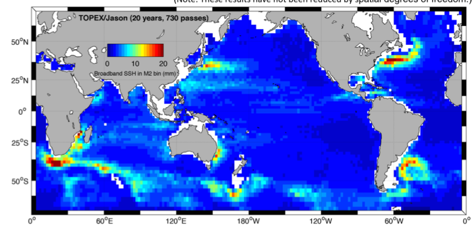


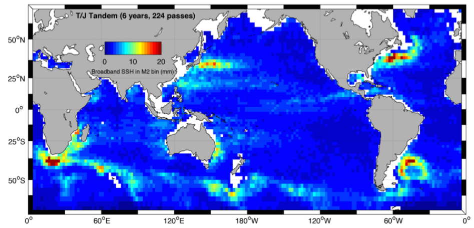
In the context of the multi-satellite analysis conducted here, it is important to question whether adding additional satellites with higher noise levels and/or fewer cycles (ERS and Geosat) improves or degrades the analysis. With the 160 km fitting regions used currently, the TOPEX track spacing is sufficient to ensure nearly-homogeneous data coverage, so little improvement or degradation is seen from the other satellites. For the smaller fitting windows used in Zhao et al (2011) near Hawaii, the additional satellites were essential, and the resulting maps did appear to show similar high-resolution beam structures in agreement with internal tide models of the region. Away from high-signal regions, the considerably higher noise levels of ERS and Geosat may cause plane-wave results to decrease in quality when they are added.

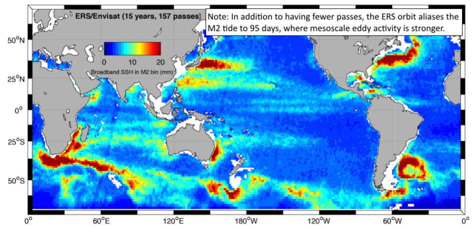


Noise: Non-tidal processes

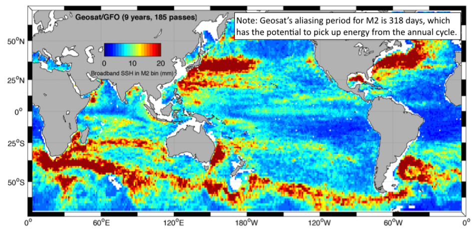
(Note: These results have not been reduced by spatial degrees of freedom.)







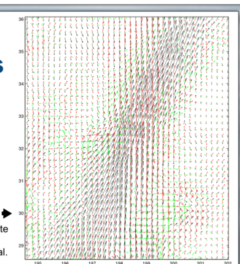
Note: In addition to having fewer passes, the ERS orbit aliases the M2 tide to 95 days, where mesoscale eddy activity is stronger.



Note: Geosat's aliasing period for M2 is 318 days, which has the potential to pick up energy from the annual cycle.

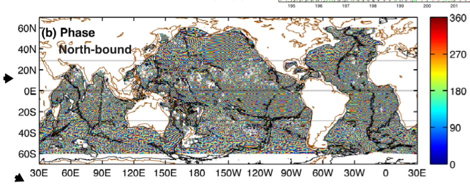
Identifying Beams and their Connection to Generation Sites

- Altimetric internal tide maps have proven to be a powerful tool for exploring the distribution of internal tide generation sites, but a great deal of the analysis to date has relied on subjective interpretations of the patterns seen. A robust algorithm for grouping adjacent fitted waves into larger-scale "beams" is an important next step.
- Because the subjectively-identified beams tend to emanate from localized generation sites, an objective method would allow global classification and quantification of these sites, leading to improved estimates of the role of internal tides in tidal energy dissipation and mixing.

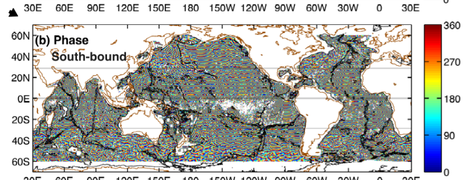


(right) Energy flux vectors for the 3 fitted waves in a region north of Hawaii. Note that colors only label the relative sizes, and not necessarily dynamically-connected beams. Automated separation of coherent beams is an ongoing goal.

(right) Phase of the largest northbound (upper) and southbound (lower) plane wave. In many regions, phase illustrates coherent wave fronts from discrete internal tide generation features and are consistent with the mode-1 wavelength used in the fitting procedure.



In locations of predominantly east-west propagation or in complex interference patterns the separation is not as effective.



Conclusions

- Internal tide mapping with satellite altimetry continues to be a valuable tool for studying these deep ocean internal waves and their energy transport.
- Uncertainty estimates using the broad mesoscale SSH spectral level show patterns similar to the "noise" in the wave-fitting results, leading to the prospect of maps including only locations with signal-to-noise ratio over a particular threshold. Remaining questions center on the degree of spatial correlation within the fitting regions.
- Patterns in the error maps for the 4 satellite types are quite similar and mirror eddy kinetic energy distributions. Differences are mostly due to the number of passes available on each track.

Acknowledgments

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