The Wavenumber Spectrum of Sea-Surface Height in the Caribbean Sea: the roles of stationary and non-stationary internal tides

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Introduction

Output from a high-resolution operational ocean model is compared with along-track altimetric sea-surface height (SSH) in order to understand processes governing the wavenumber spectrum of SSH, particularly the dual roles of tidal internal waves and mesoscale variability. The Caribbean Sea is the focus of study because it contains several tidal internal wave generation sites and a relatively homogeneous mesoscale eddy field. Tides, while small, influence the SSH spectrum slope at scales smaller than 150km, with contributions from both the stationary (phase-locked) and non-stationary internal tides. Causes and consequences of incoherent tides are diagnosed in the model with consideration of their significance in future wide-swath altimeter missions.

The AMSEAS Model

- 3km-resolution implementation of the Navy Coastal Ocean Model (NCOM), covering the Gulf of Mexico, Caribbean Sea, and Western Atlantic.
- Free-surface, hydrostatic, Boussinesq, and incompressible – based on the Princeton Ocean Model (POM) and the Sigma/Z-Level Model.
- 55 vertical layers – sigma levels down to 550m and z-levels below that to 5000m.
- Routine forecasts were initiated in May 2010.
- The two-year period, June 2010 through June 2012, used here.
- Air-sea momentum and heat fluxes from FNMOC Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS).
- Open boundary conditions taken from the Global NCOM model.
- Boundary conditions are augmented with tidal elevations (M_f, M_m, K_1, O_1, P_1, Q_1, M_2, S_2, N_2, K_2) from Egbert et al TPXO7 model.
- Data assimilation via Cummings et al NCODA system.
- 96-hour forecasts produced daily with output archived at 3-hour intervals.

Observed and Modeled SSH

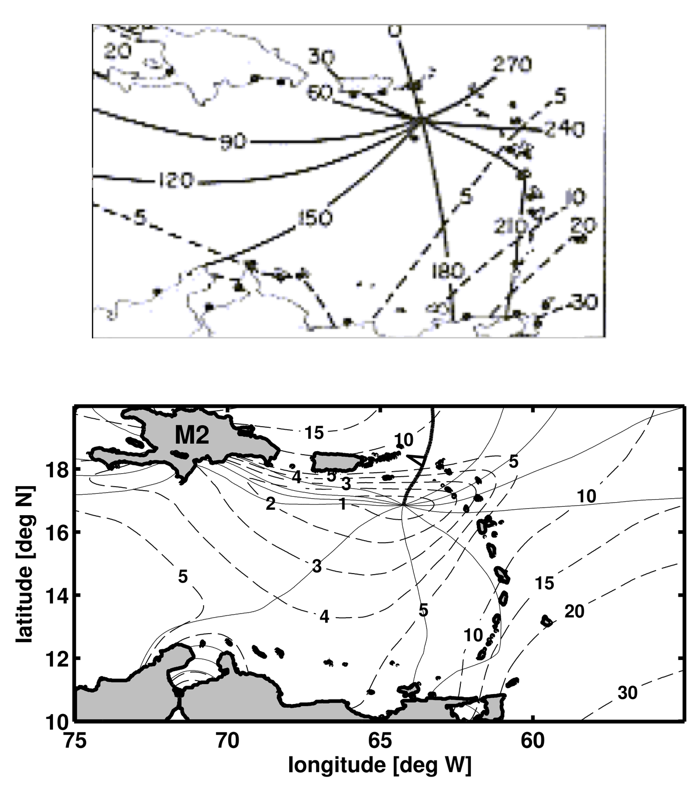

Figure 1: Top: M_2 cotidal chart from Kjerfve (1981), based on island gauges. Bottom: Spatially low-passed M_2 tide from AMSEAS.

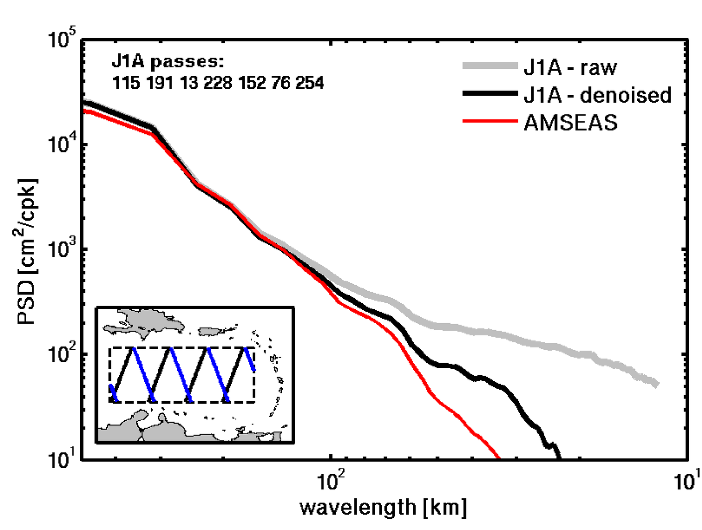

Figure 2: Model vs. JASON-1 altimeter wavenumber spectra, based on data from 2002–2009.

OBSERVATIONS

- Shallow, k^{-2}, SSH spectrum is observed in model and data.
- Reasonable barotropic tides, errors increase to west.
- Baroclinic tides disagree in detail, but appear to be of correct magnitude.

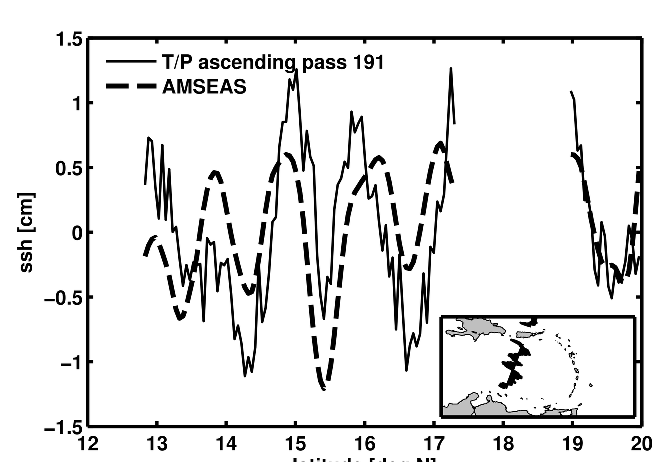

Figure 3: Surface expression of M_2 internal tide along TOPEX pass 191.

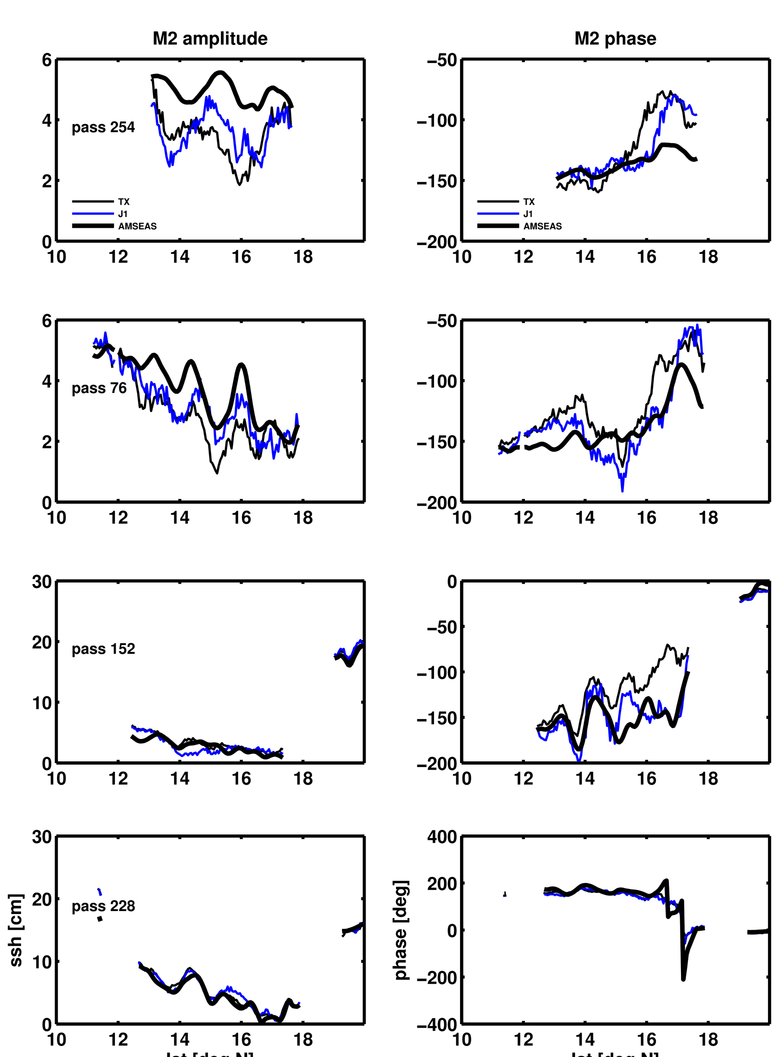

Figure 4: Model vs. altimeter, M_2. Tidal amplitude (left) and phase (right) for TOPEX and JASON-1 altimeters (thin lines) compared with AMSEAS (thick black line). Descending orbit passes are ordered from west to east.

Significance of Tides in the AMSEAS SSH Spectrum

Although tides and internal tides are relatively small in the Caribbean Sea, tidal peaks are evident in azimuthally-averaged two-dimensional power spectra.

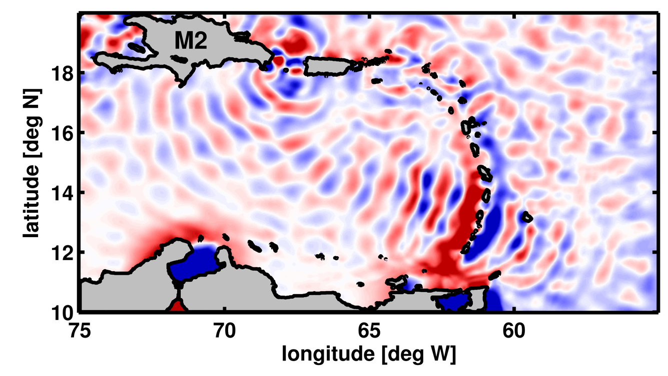

Figure 5: Spatially high-passed M_2, quadrature component. Color scale from -3cm (blue) to $+3$cm (red).

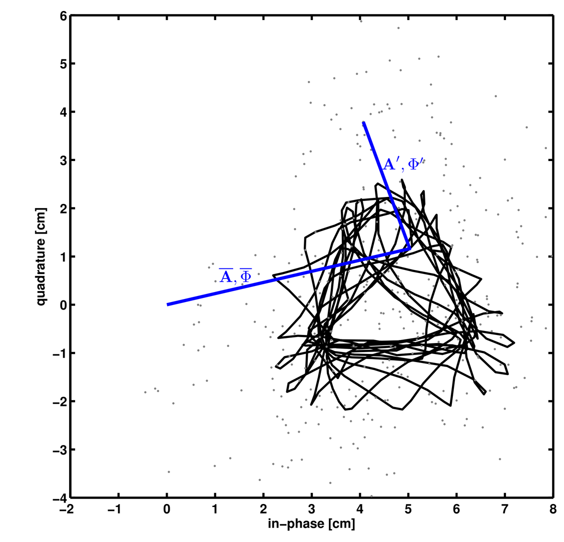

Figure 6: Interactions of tides at frequencies which cannot be resolved from 96-hour analysis creates apparent, but predictable (stationary), tidal modulation, $\overline{A}, \overline{\Phi}$ (solid black line). Non-stationary tides are those defined by harmonic analysis which cannot be explained by predicted modulations, $A'\Phi'$.

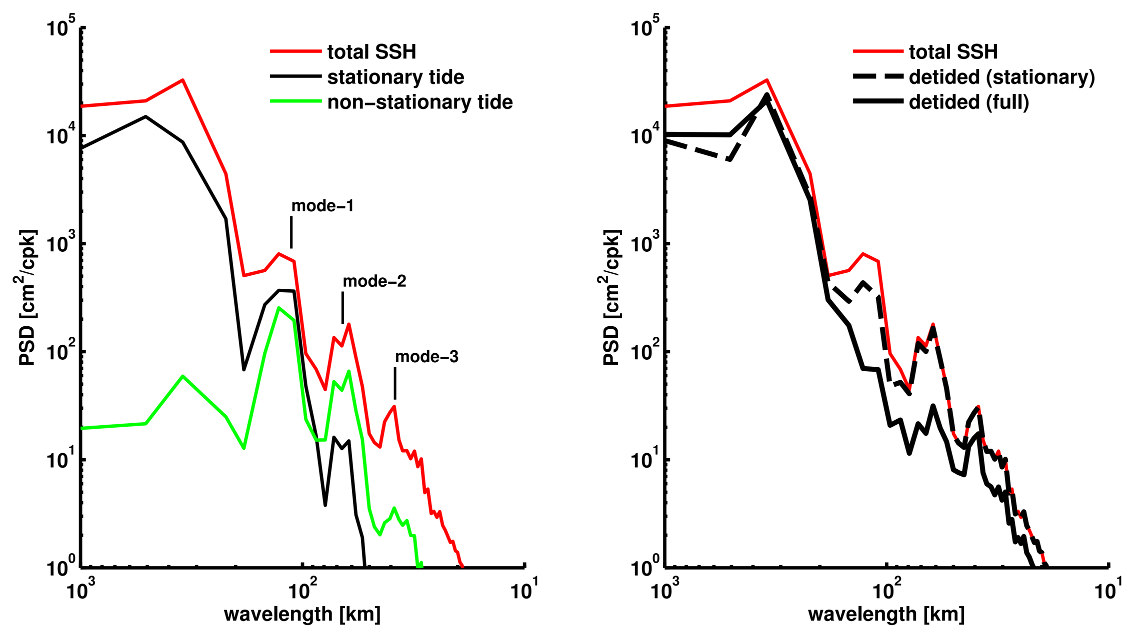

Figure 7: Radial wavenumber spectrum, AMSEAS.

OBSERVATIONS

- Unlike along-track spectra, internal tide peaks are resolved by radial spectra.
- Mode-1 (109km; 2.5m/s): ratio of stationary to non-stationary variance is nearly 2:1.
- Mode-2 (65km; 1.5m/s): ratio of stationary to non-stationary variance is 1:4.
- Mode-3 (38km; 0.86m/s): tide decorrelates from forcing within 96hr.

Causes of Non-Stationary Tides

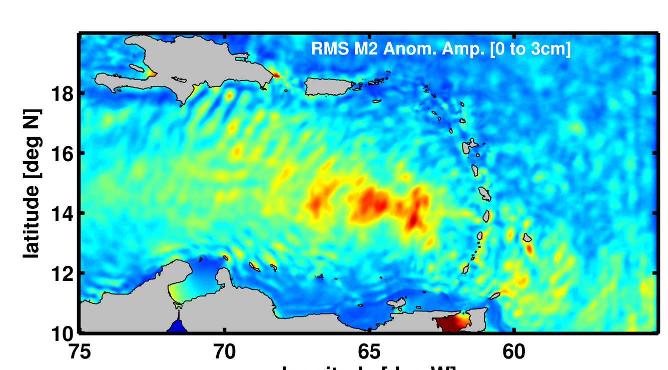

Figure 8: Non-stationary M_2 amplitude

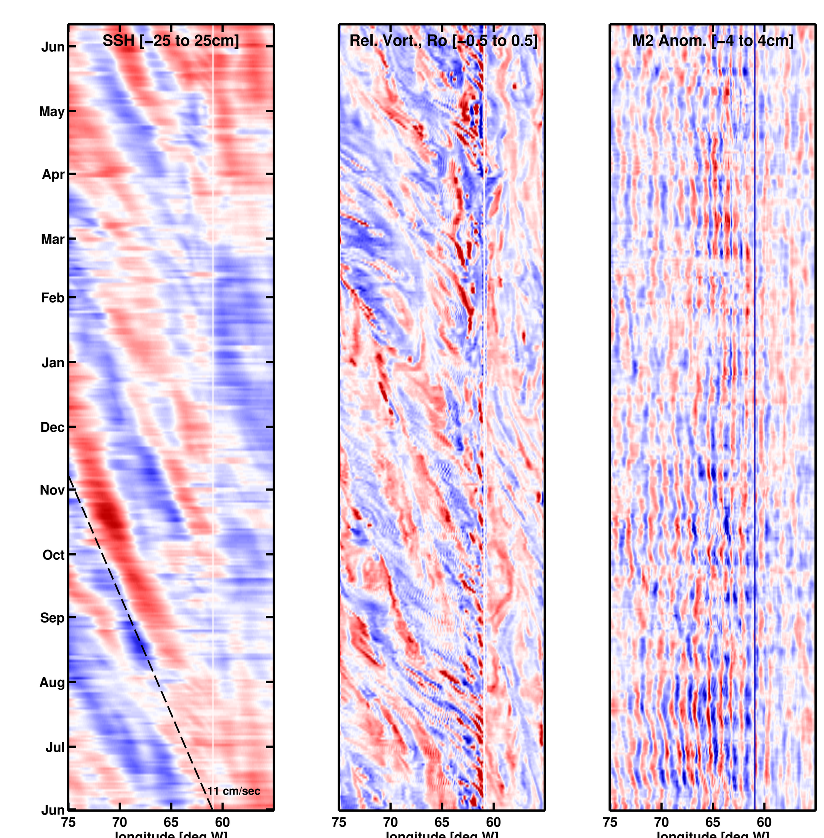

Figure 9: Hovmöller diagram for 2010–2011 across 14°N: subtidal SSH (left), geostrophic relative vorticity (center), quadrature component of non-stationary tide (right).

OBSERVATIONS

- Refraction due to relative vorticity and Doppler effects may contribute locally, but not on large scales.
- Resolved (mode-1 and mode-2) non-stationarity arises from both propagation effects and generation-site changes.

Discussion & Conclusions

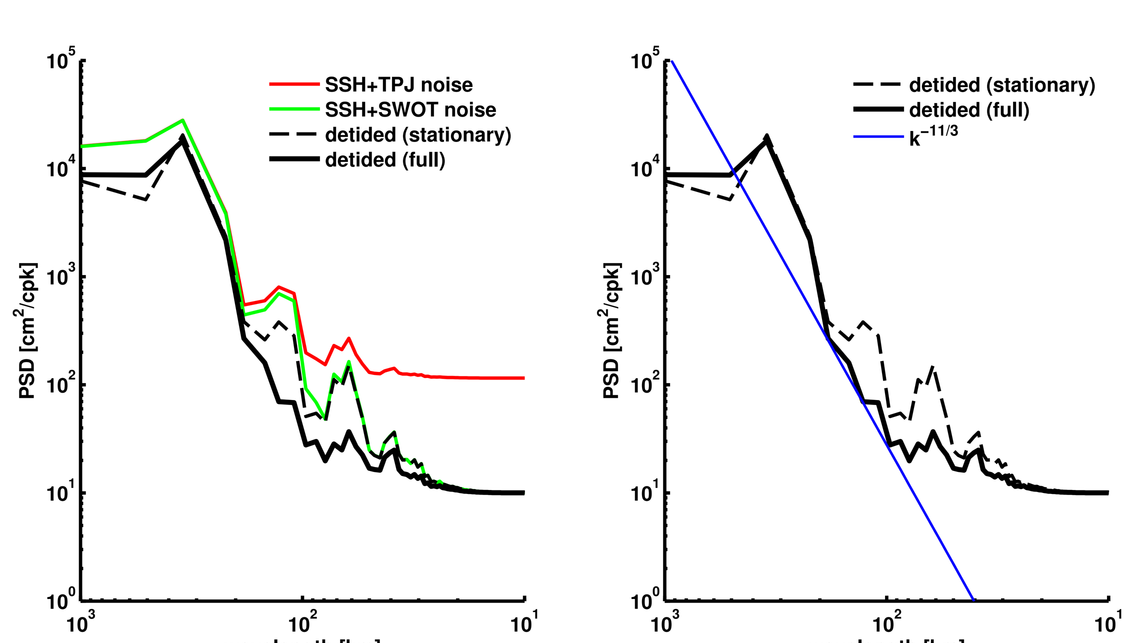

Figure 10: Hypothetical radial wavenumber spectrum for the Caribbean Sea, TPJ and SWOT.

- Internal tides will be well-resolved by the anticipated SWOT mission.
- In the Caribbean Sea a steeply sloped $k^{-11/3}$ spectrum indicative of surface quasi-geostrophic dynamics is "hidden" below the internal tide SSH spectrum.
- Even if it can be estimated, removal of the stationary internal tide is not sufficient to observe the $k^{-11/3}$ spectrum; the non-stationary tides must also be removed.
- The shallow slope of the observed along-track SSH spectrum in the Caribbean Sea is caused by a combination of tidal internal waves and altimeter noise.

Acknowledgements

Frank Bub (Naval Oceanographic Office) and John Harding (Northern Gulf Institute) publish the AMSEAS model output in near-real time as a public service.[1] The satellite altimeter data, orbits, and environmental corrections were extracted from the Radar Altimeter Database System (RADS).[2] The TPXO7 tidal model is created and distributed by Egbert et al (OTIS).[3]

[1] http://edac-dap.northerngulfinstitute.org/
[2] http://rads.tudelft.nl/rads/rads.shtml
[3] http://volkov.oce.orst.edu/tides/otis.html