The Mode-2 M_2 Internal Tide

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1. Data and Methods

The mode-2 M_2 internal tide can be detected via its sea surface height (SSH) signals by satellite altimetry. Here a global map is constructed using 25 years (1992–2017) of SSH measurements made by multiple altimeter missions. It is extracted in two steps: First, the mode-2 component is separated from modes 1 and 3 (Fig. 1) by a bandpass filter with cutoff wavelengths of [0.85 1.35] times the local mode-2 M_2 wavelength (Fig. 2); second, 3 mode-2 waves are extracted by fitting plane waves in each 120 km by 120 km window (Fig. 3). The result is verified using 4 years (2011–2014) of independent Cryosat-2 data (Fig. 4).

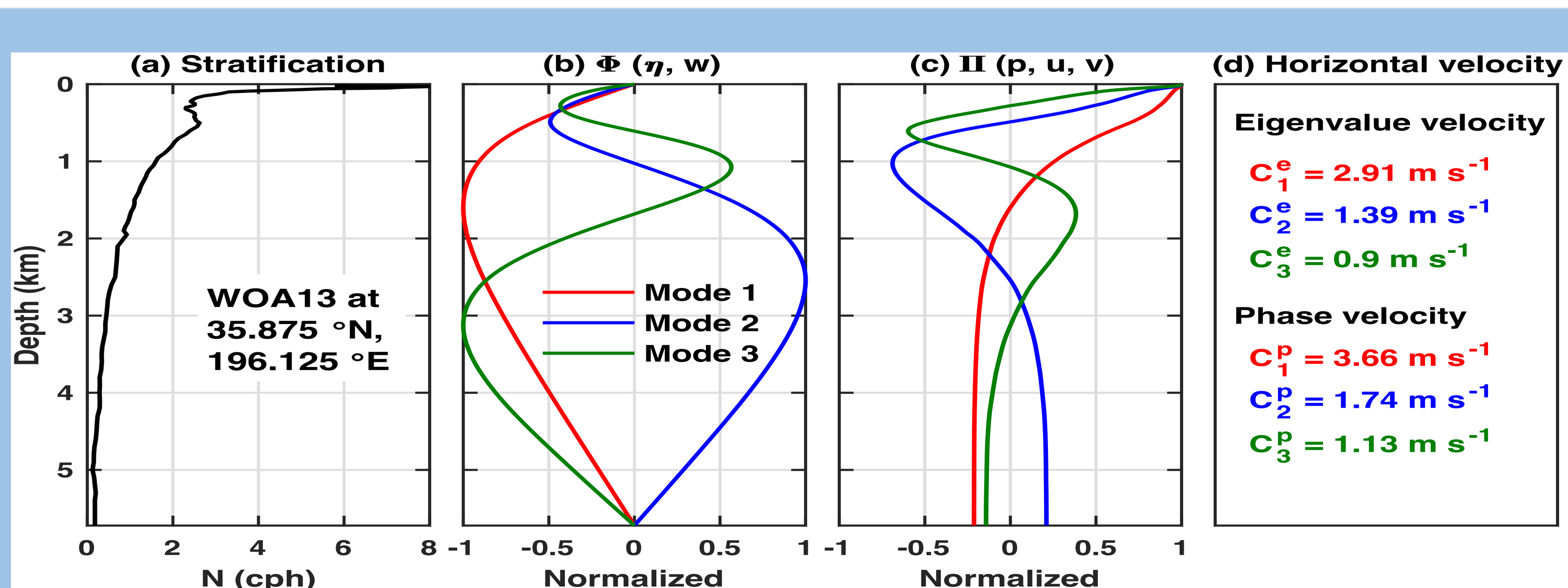


Figure 1. Stratification profile and baroclinic modes. (a) A stratification profile from WOA13. (b, c) Baroclinic modes solved using the Sturm-Liouville equation. (d) Horizontal velocities of mode-1–3 M_2 internal tides.

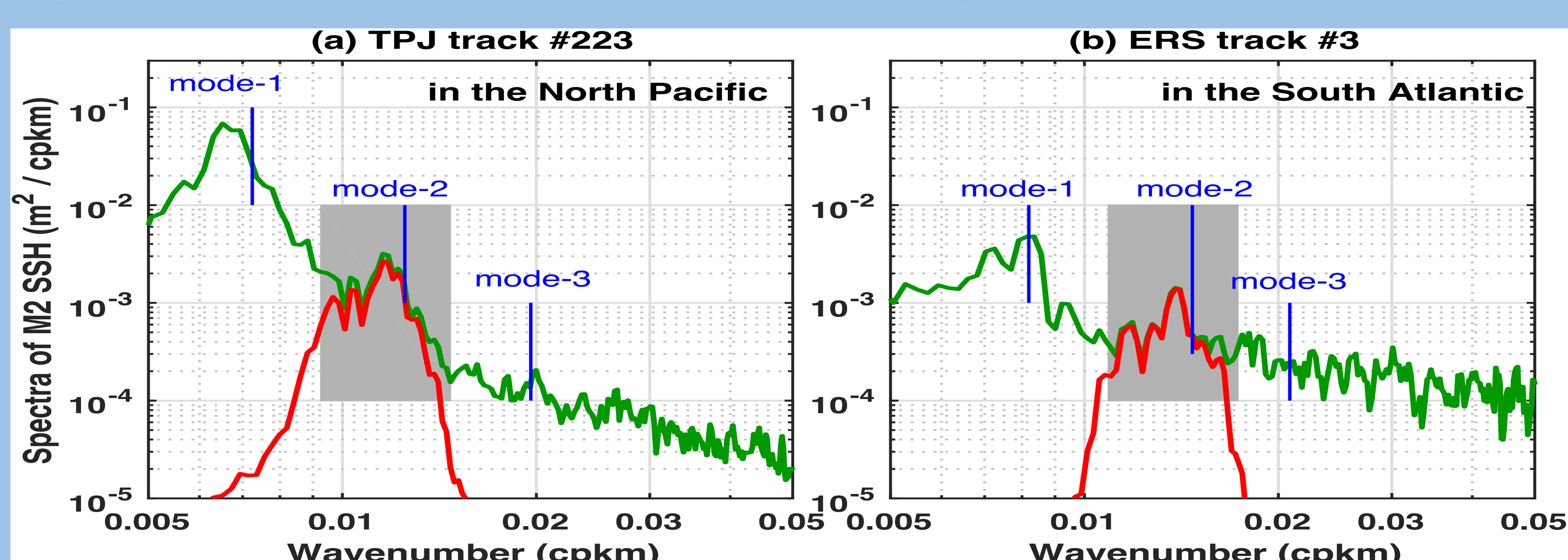


Figure 2. Along-track wavenumber spectra of the M_2 internal tide SSH (green), theoretical wavelengths (blue), and bandpass filters (gray). (a) Along TPJ track #223. (b) Along ERS track #3.

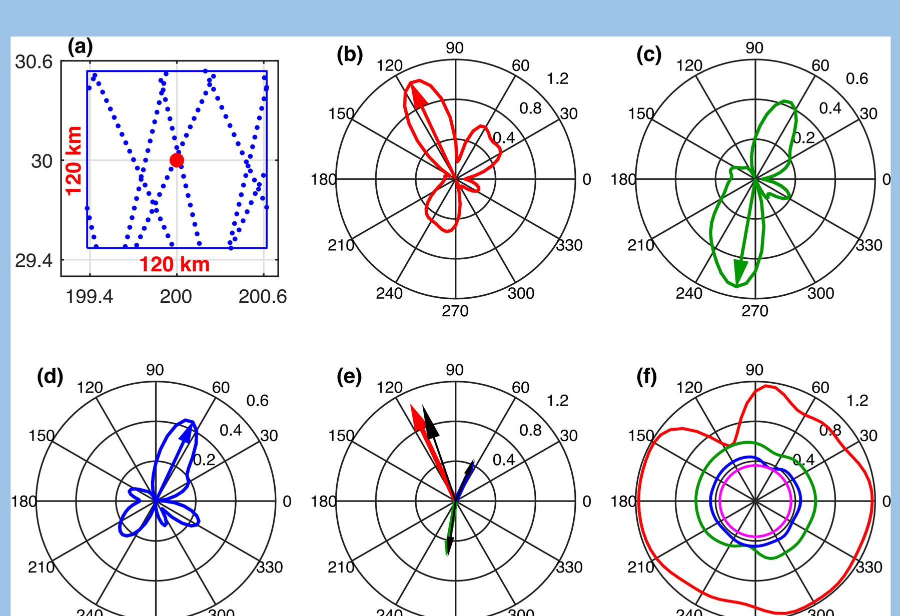


Figure 3. Mode-2 M_2 internal tidal waves are extracted by plane wave analysis. (a) Positions of SSH data in a 120 km by 120 km window centered at 30N, 200E. (b) SSH amplitude (unit: mm) versus direction obtained by fitting a plane wave in each compass direction. The first mode-2 M_2 internal tidal wave (red arrow) is determined from the largest lobe. (c) After removing the first wave, this procedure is repeated to determine the second wave (green arrow). (d) After removing the first and second waves, this procedure is repeated to determine the third wave (blue arrow). (e) Each wave is refitted with the other two waves temporarily removed. Black arrows are the finally determined three internal tidal waves. (f) Variance reduction (unit: mm^2) with the removal of each wave.

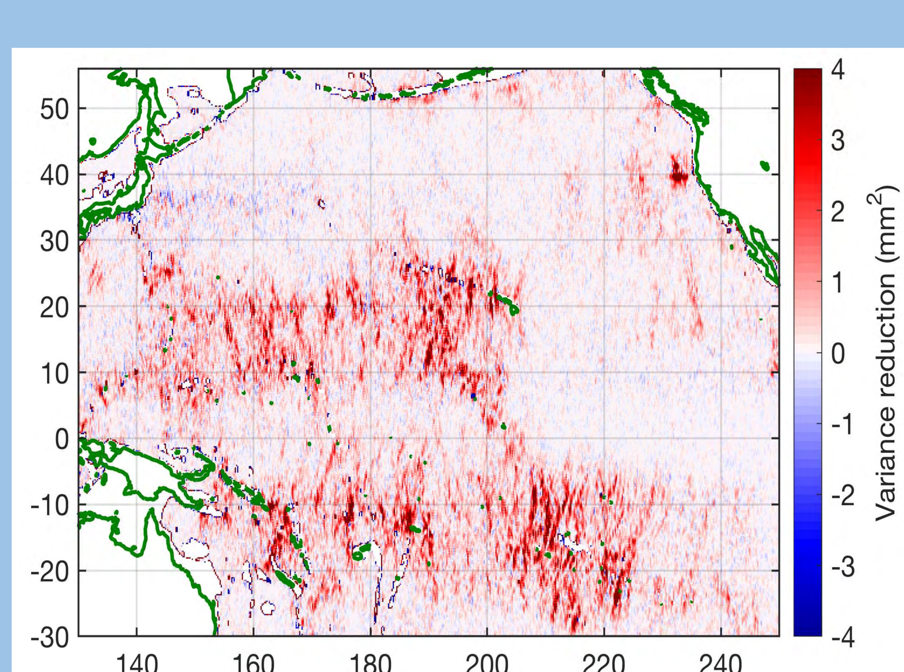
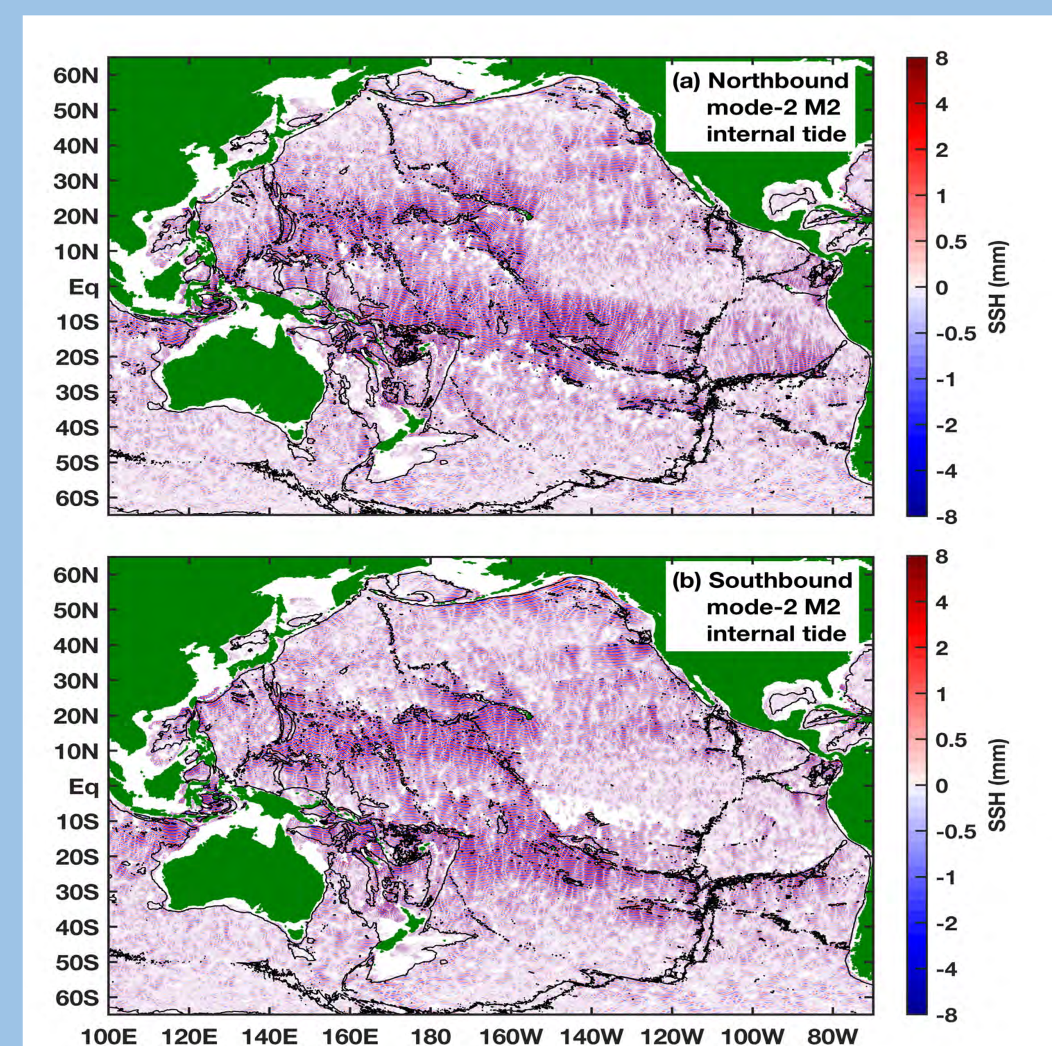


Figure 4. SSH variance reduction in 0.6° by 0.6° bins. It is obtained by correcting the mode-2 M_2 internal tide in 4 years (2011–2014) of independent Cryosat-2 data using the mode-2 model constructed using 25 years (1992–2017) of multi-satellite altimeter data. See Figures 5 and 6 for the mode-2 M_2 model.

2. Global and Regional Maps

The satellite results reveal rich information on the global mode-2 M_2 internal tide. Figures 5 and 6 show that the mode-2 M_2 internal tide is ubiquitous in the ocean and its SSH amplitudes are O (1 mm). Figures 7 and 8 show that the spatial patterns of mode-1 and -2 internal tides are VERY different. Mode 1 mainly originates at steep topographic features such as submarine ridges, but mode 2 is also generated at gentler topographic features such as abyssal seamounts and fracture zones. Mode-1 beams propagate O (1000 km), while mode-2 beams can be tracked for O (100 km). The globally integrated energy of the mode-2 M_2 internal tide approximates to 8 PJ, about 22% of mode 1 (36.4 PJ). These results imply that higher-mode internal tides may play an important role in the tidal energetics, in particular, over abyssal seamounts and fracture zones.



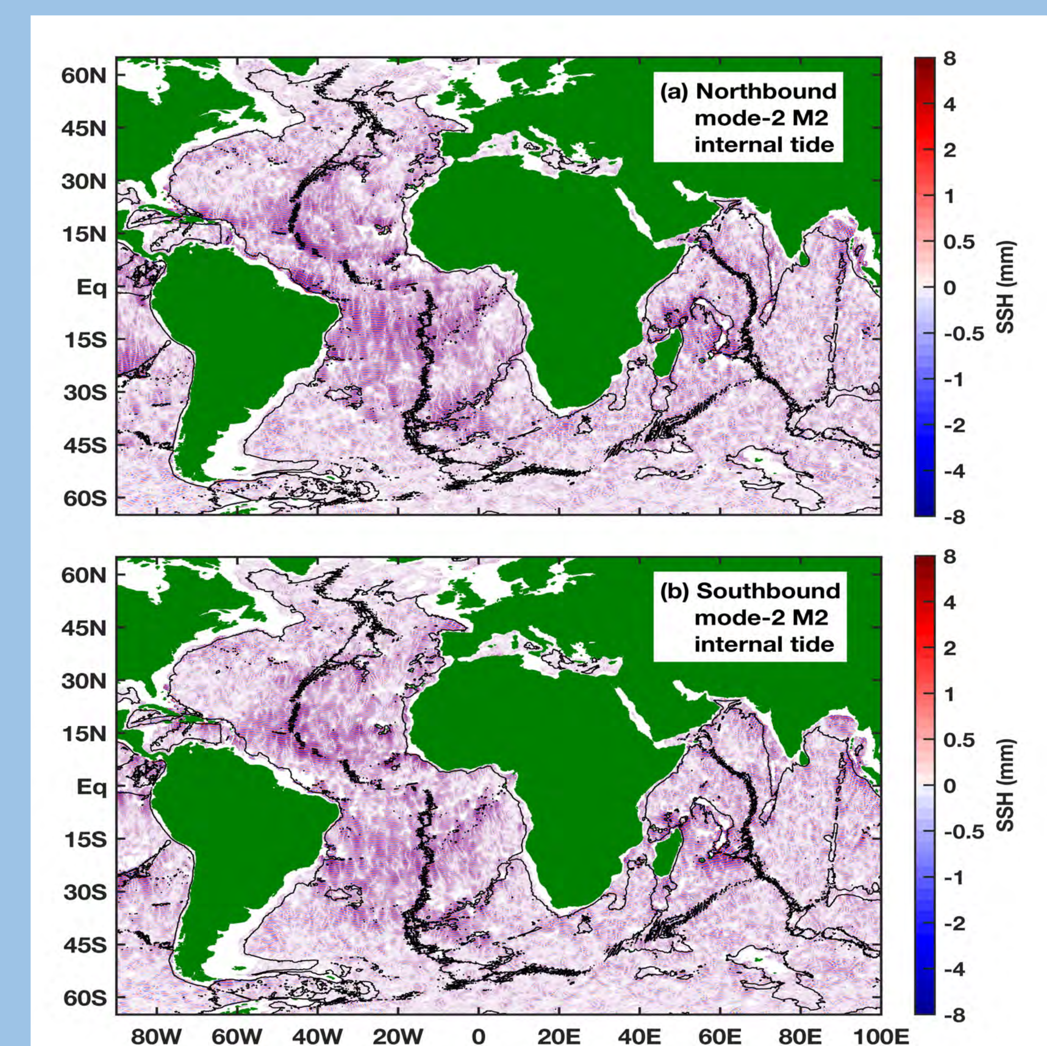
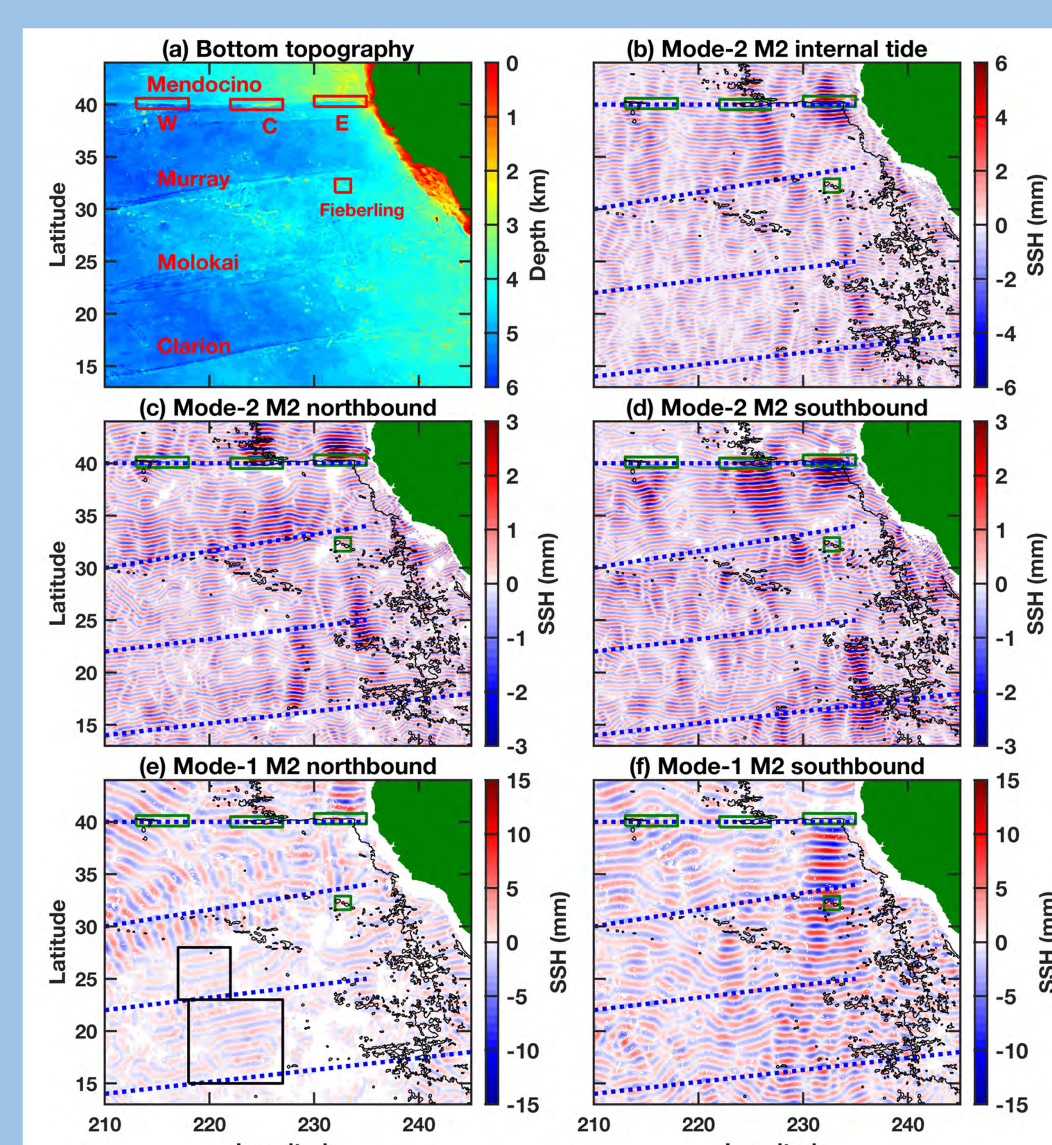
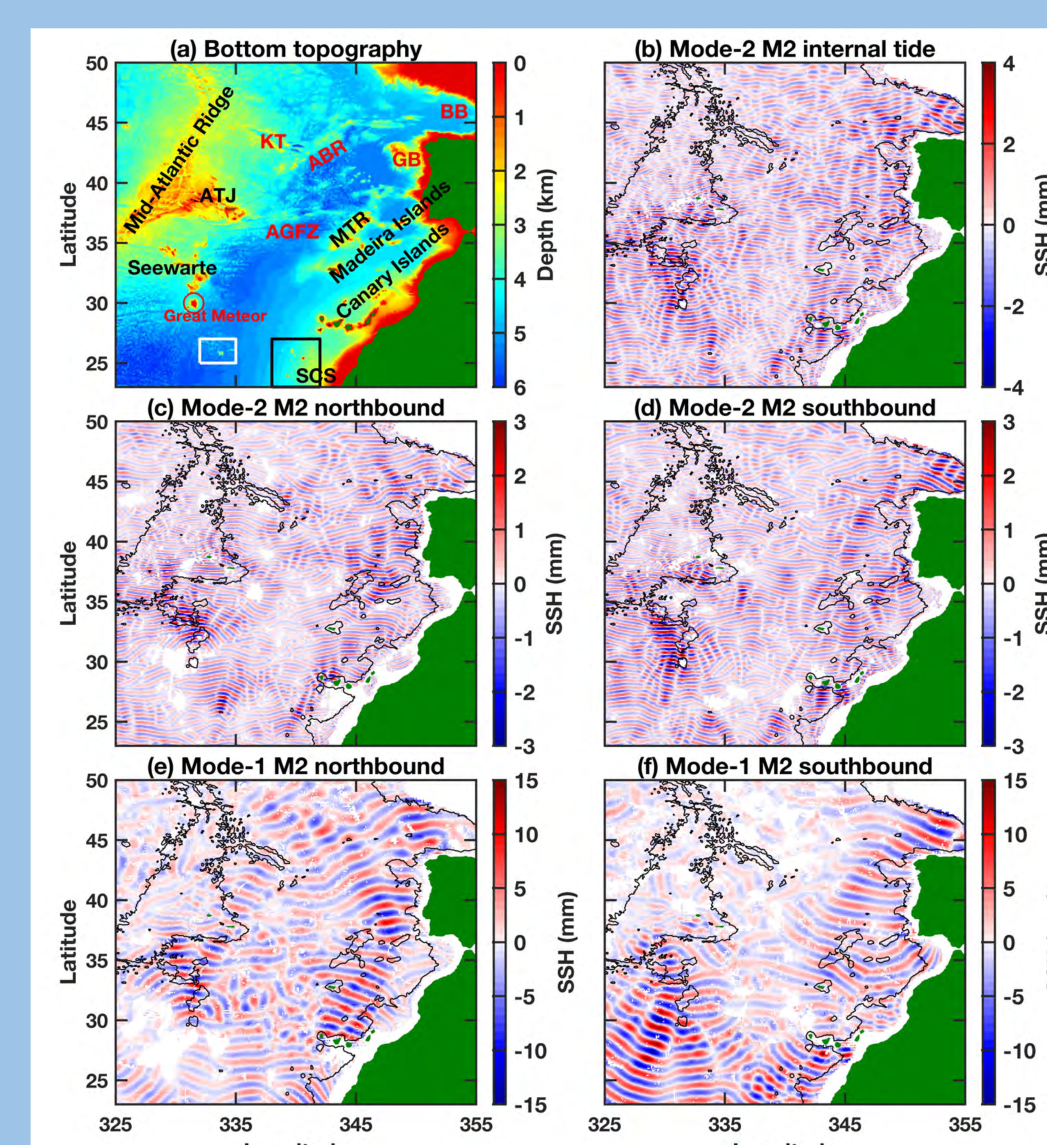


Figure 5 (left panels). The mode-2 M_2 internal tide in the Pacific Ocean. (a) Northbound component (propagation direction ranging 0–180). (b) Southbound component (propagation direction ranging 180–360). The SSH amplitudes are shown in logarithmic scale. SSH values lower than 0.1 mm are not shown. The 3000-m isobath contours are in black. **Figure 6 (right panels).** The mode-2 M_2 internal tide in the Atlantic and Indian Oceans.





Figures 7 (left). The M_2 internal tide in the eastern North Pacific Ocean. (a) Bottom topography. This region features four fracture zones. Fieberling Seamount is also labeled. (b-d) Mode-2 M_2. (e-f) Mode-1 M_2. The 3000-m isobath contours are in black. **Figure 8 (right)**. As in Figure 7 but for the eastern North Atlantic Ocean.

3. Issues and Future Work

- The present satellite results contain the phase-locked (missing time-varying) and southbound/northbound (missing eastbound/westbound) component only. Much work is needed to address these issues.
- Construct mode-2 M_2, S_2, O_1 and K_1 internal tides.
- Compare with independent satellite data, mooring measurements, and numerical model outputs.
- Quantify energetics of the mode-2 internal tide and its resultant ocean mixing.
- **Reference: Zhao, Z (2018), The global mode-2 M_2 internal tide, JGR Oceans, doi:10.1029/2018JC014475.**