Satellite Estimates of Mode-1 M_2 Internal Tides using Nonrepeat Altimetry Missions

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Introduction

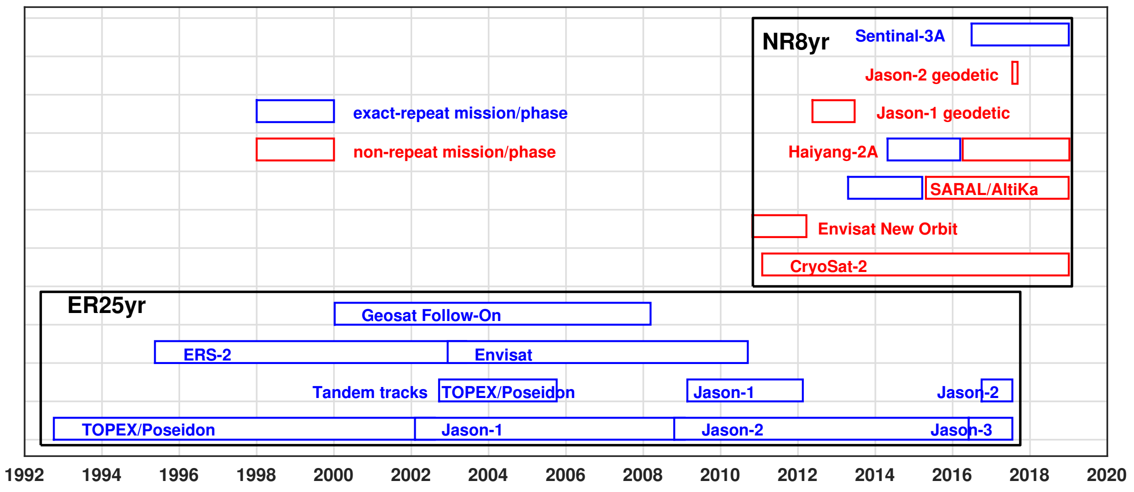
Previous satellite estimates of internal tides are usually based on 25 years of sea surface height (SSH) data from 1993 to 2017 measured by exact-repeat (ER) altimetry missions. In this study, new satellite estimates of internal tides are based on 8 years of SSH data from 2011 to 2018 measured mainly by nonrepeat (NR) altimetry missions. The two datasets are labeled ER25yr and NR8yr, respectively.

Mode-1 M_2 internal tides can be mapped using 8 years of data made by nonrepeat altimetry missions. NR8yr has advantages over ER25yr in observing internal tides, because of its shorter time coverage and denser ground tracks. The impact of window size and time coverage can be examined.

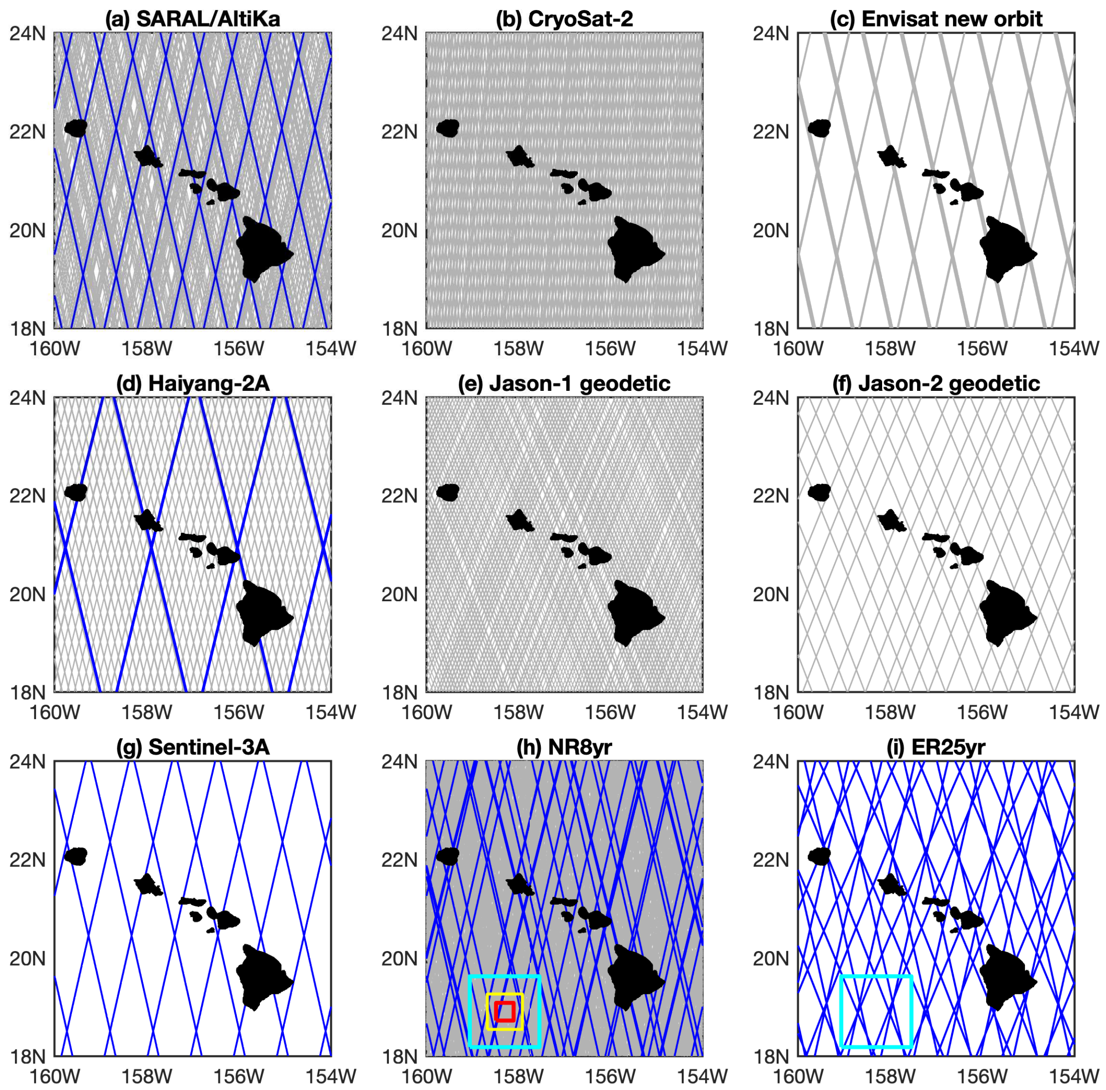
Comparing models mapped from the two altimetry datasets sheds new light on the spatiotemporal variability of internal tides. A few regions with significant interannual variability are identified.

The impact of window size is also examined using the HYCOM simulated high-resolution internal tide field. The size of fitting window is an important parameter for decomposing internal tide fields.

Data



(upper) The time coverage of satellite altimetry data used in this study. Red and blue indicate nonrepeat and exact-repeat altimetry missions (phases), respectively.



(left) Ground tracks of the altimetry missions around Hawaii. Exact-repeat and nonrepeat missions (phases) are in blue and gray, respectively. The cyan, yellow, and red boxes indicate 160-, 80-, and 40-km fitting windows, respectively. Due to sparse tracks, M_2 internal tides are mapped from ERS25yr using 160-km windows only.

Methods

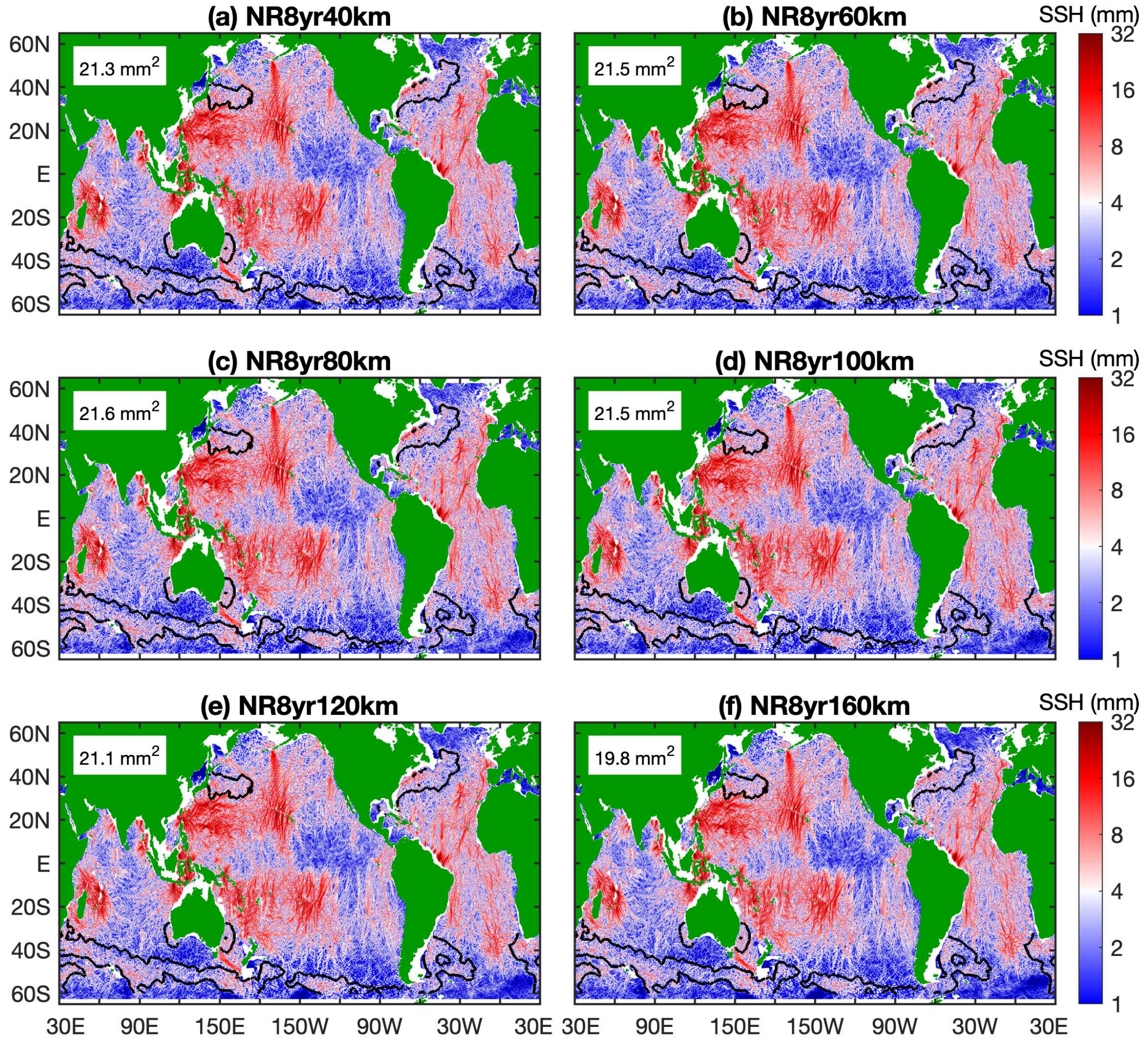
M_2 internal tides are mapped from the two SSH datasets following the same three-step procedure, which consists of two rounds of plane wave analysis with a spatial bandpass filter in between. This mapping technique has been developed and employed in our recent studies. Table 1 lists the three steps and some key parameters.

NR8yr has denser ground tracks, so that mode-1 M_2 internal tides can be mapped using small windows. Six different windows are used in the first-round plane wave analysis: 40, 60, 80, 100, 120, and 160 km (Table 1). The six internal tide models are labeled as NR8yr40km, NR8yr60km, NR8yr80km, NR8yr100km, NR8yr120km, and NR8yr160km, respectively. ER25yr has sparse ground tracks, so that mode-1 M_2 internal tides are mapped using 160-km windows only. The resultant model is labeled ER25yr160km.

TABLE 1. The mapping procedure. Mode-1 M_2 internal tides are mapped from NR8yr and ER25yr following the same procedure and using the same parameters, except for different windows in the first step. Six different windows are used for NR8yr and only the 160-km window is used for ER25yr. The wavenumber of mode-1 M_2 internal tides K(lon, lat) is calculated using the hydrographic climatology in the *WOA13*.

Procedure	Operation	Key parameters
Step 1	Plane wave analysis	0.2° × 0.2° spatial grid; 40-, 60-, 80-,100-, 120- and 160-km window; 5 waves
Step 2	Spatial bandpass filter	850-km window; bandpass cutoff wavenumbers are [0.75 1.50] × K(lon, lat)
Step 3	Plane wave analysis	0.2° × 0.2° spatial grid; 100-km window; 5 waves

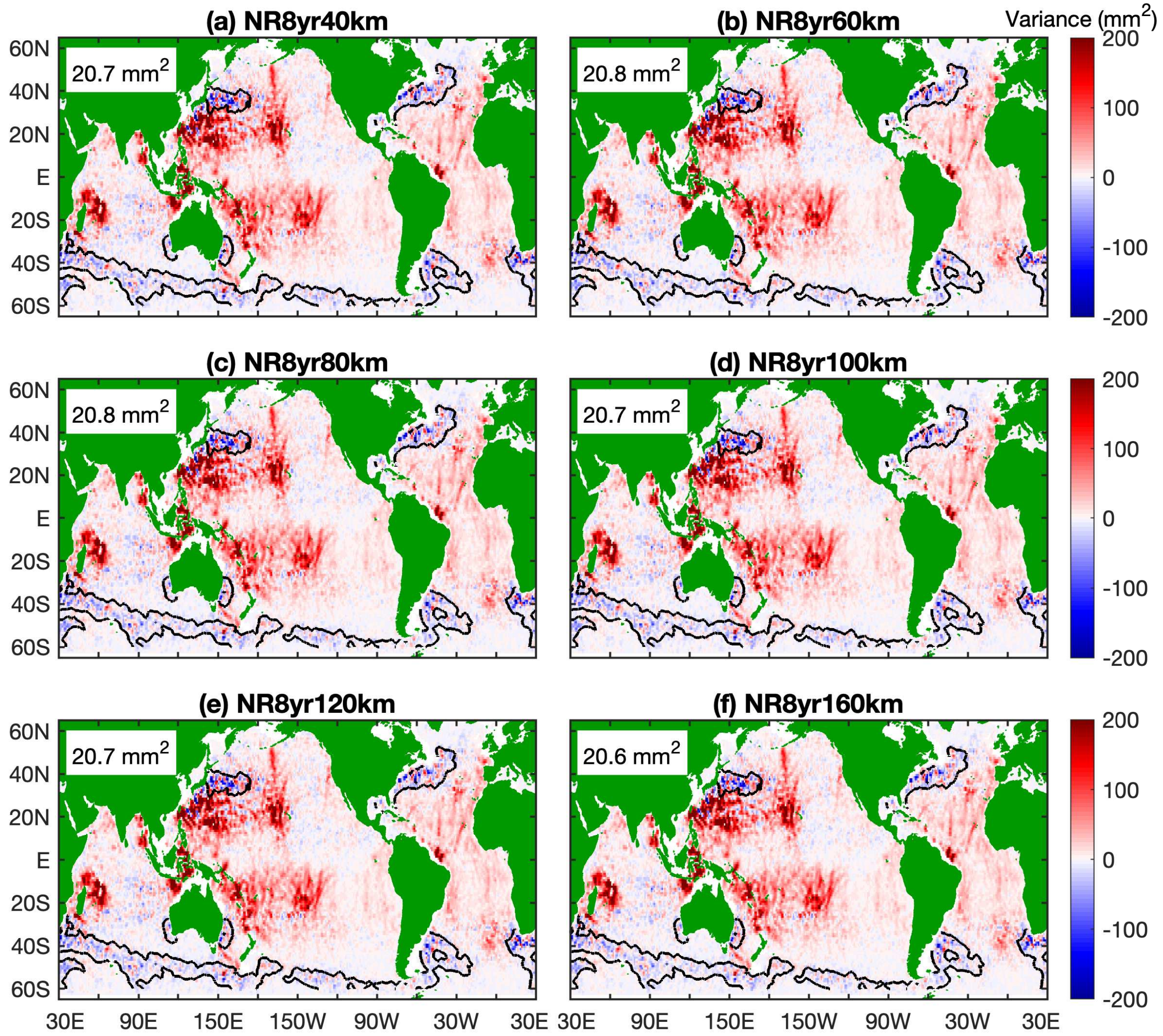
Results



Six mode-1 M_2 internal tide models from NR8yr. Shown are their SSH amplitudes in logarithmic scale. Internal tides in shallow ocean (<1000 m) are discarded (blank). The black contours indicate regions of strong currents, where the satellite altimetric internal tides are noisy. Their global mean variances are calculated and given (excluding regions of strong currents). Their global mean model variances are very close.

The six models have similar spatial patterns. They all demonstrate the basic features of the global mode-1 M_2 internal tide field. There are energetic M_2 internal tides around the Hawaiian Ridge, around the French Polynesian Ridge, in the western Pacific Ocean, in the Madagascar–Mascarene region, and in the Indonesian Seas. These models are consistent with previous observations from satellite altimetry by other researchers.

Model evaluation

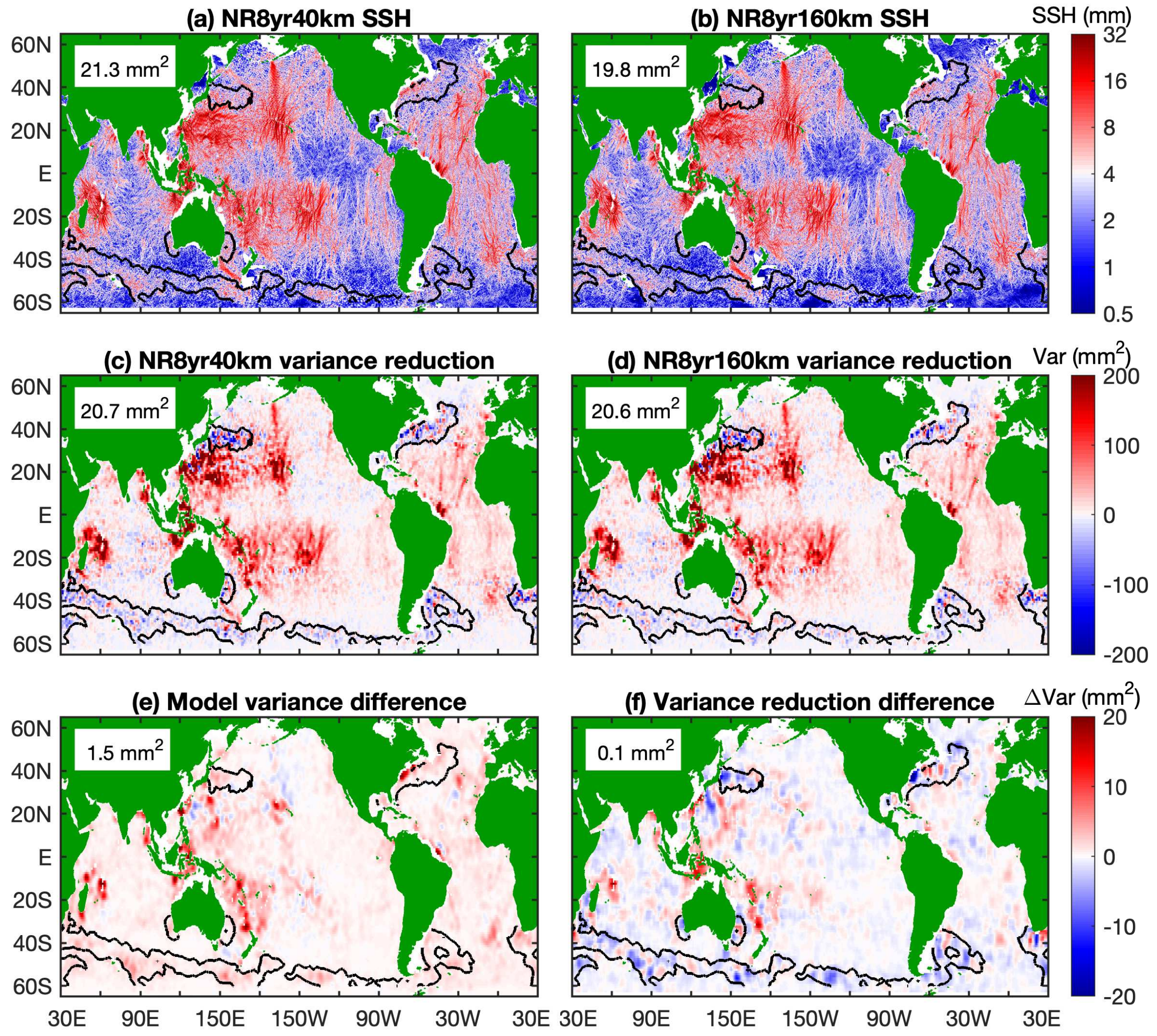


The six models are evaluated using the satellite altimetry data in 2020. The 2020 data are merged from six missions. The evaluation method has been used in previous studies. For each SSH measurement of known time and location, the internal tide signal is predicted using the model under evaluation, and subtracted from the raw satellite data. The variance reduction is the difference before and after the internal tide correction. The variance reductions for all SSH measurements are binned into half-overlapping 2-deg by 2-deg windows.

Red (positive reduction) indicates the model works well. Large variance reductions are in regions of strong internal tides such as around the Hawaiian Ridge, the Polynesian Ridge, and in the western Pacific Ocean. The results are consistent with results of other researchers.

The six models have similar performances in making internal tide correction, suggesting that mode-1 M_2 internal tides can be extracted in windows as small as 40 km by 40 km.

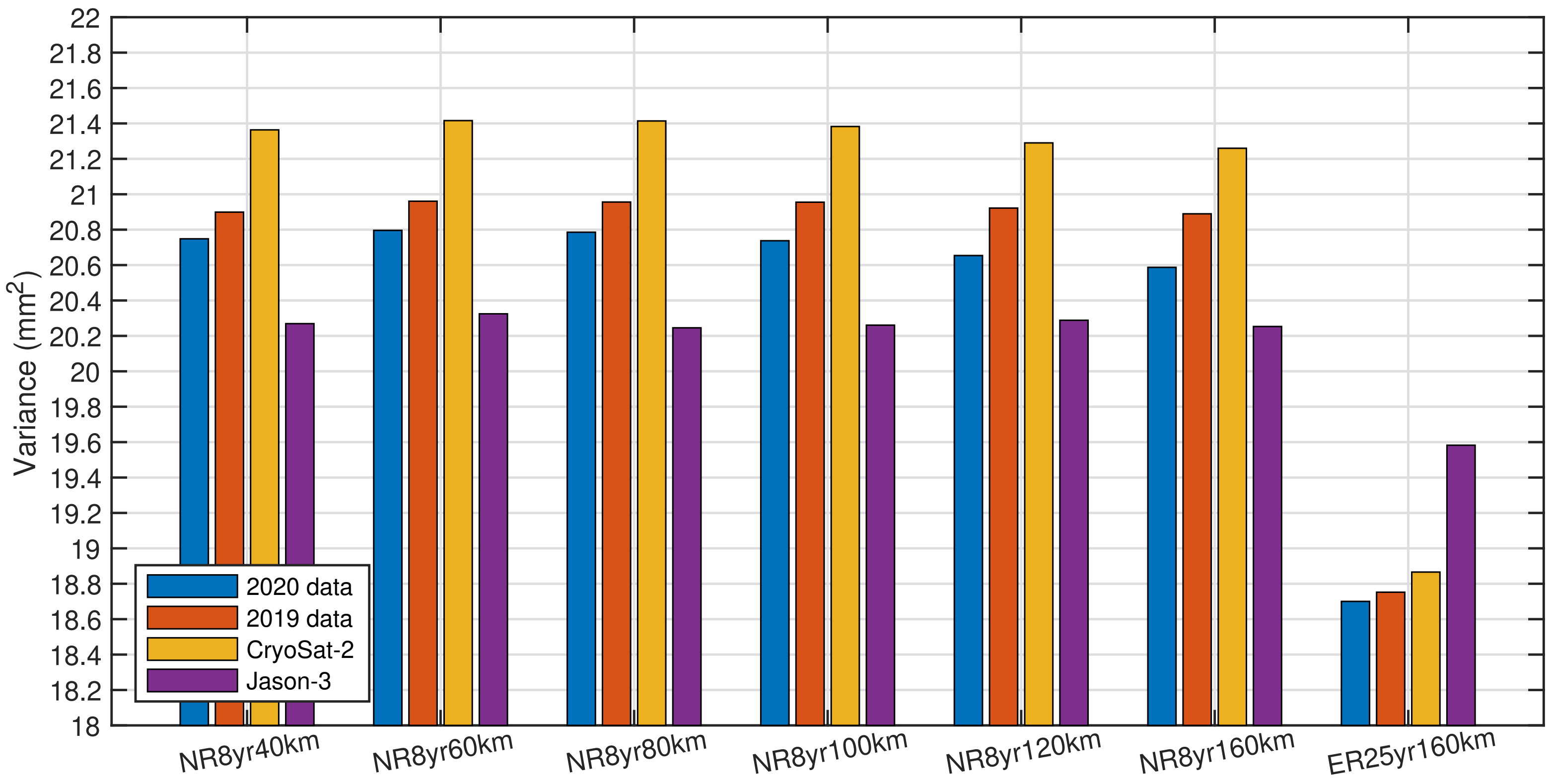
Impact of window size



Mode-1 M_2 internal tide models NR8yr40km and NR8yr160km. (a),(b) SSH amplitudes shown in logarithmic scale. Internal tides in shallow ocean (<1000 m) are discarded (blank). The black contours indicate regions of strong currents, where the satellite altimetric internal tides are noisy. Their global mean variances are calculated and given (excluding regions of strong currents). (c),(d) Model evaluation using the satellite altimetry data in 2020. Shown are variance reduction obtained by making internal tide correction. Their global mean variance reductions are calculated and given (excluding regions of strong currents). (e) Model variance difference of NR8yr40km minus NR8yr160km. (f) Variance reduction difference of NR8yr40km minus NR8yr160km.

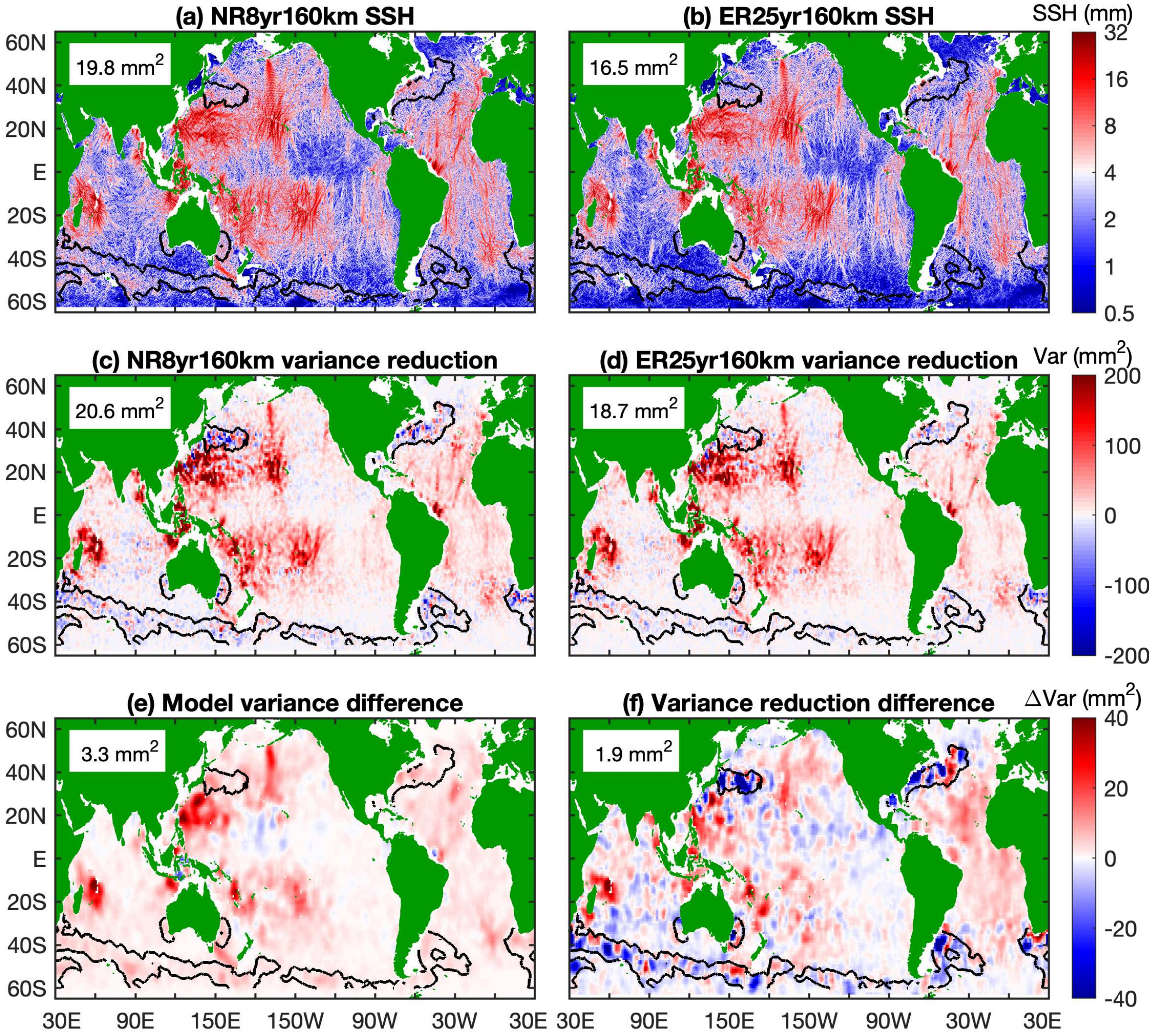
The impact of window size is a function of location. It is a trade-off of competing internal tides and background noise. For the 8 years of nonrepeat altimetry data, the small 40-km window slightly improves the internal tide model in strong source regions, but slightly worsens in regions of weak internal tides.

Evaluation using independent data



A histogram of global mean variance reductions of seven internal tide models. Four different data sets are used. The 2020 data are from six missions in 2020 (Sentinel-3A, Sentinel-3B, Jason-3, Haiyang-2B, CryoSat-2, and SARAL/AltiKa). The 2019 data are from six missions in 2019 (Sentinel-3A, Sentinel-3B, Jason-3, Haiyang-2A, CryoSat-2, and SARAL/AltiKa). The CryoSat-2 data are from 2019 and 2020. The Jason-3 data are from 2019 and 2020. This figure shows that (1) internal tide models from NR8yr have similar performances, and (2) The NR8yr models perform better than ER25yr160km. The TOPEX/Poseidon-Jason-1/2/3 data from 1993 to 2017 are used in developing ER25yr160km. The Jason-3 data in 2019 and 2020 are along the same ground tracks. Therefore, ER25yr160km reduces a little more variance in the Jason-3 data than in other data sets (purple).

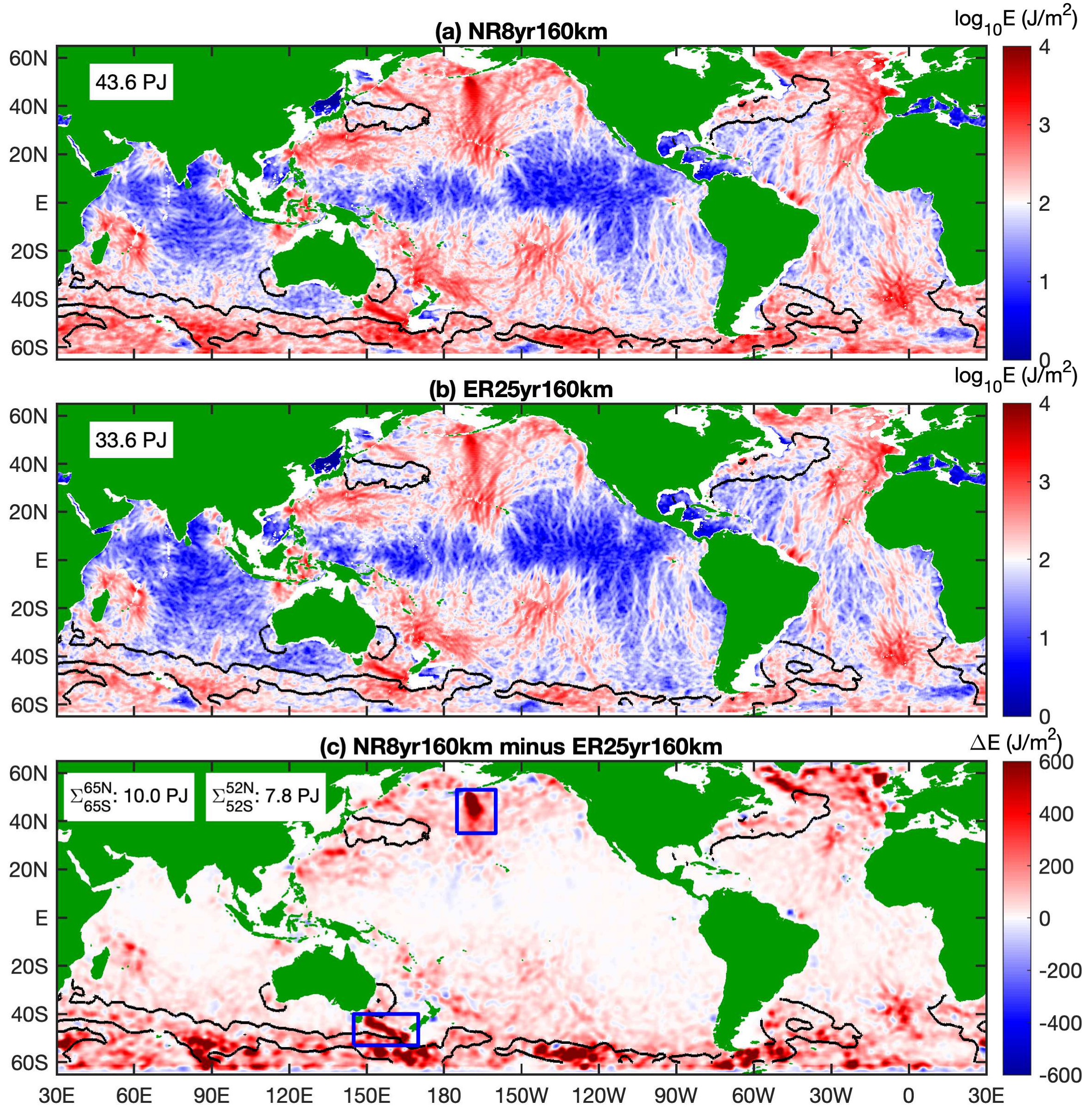
Impact of time coverage



The impact of time coverage is studied by comparing NR8yr160km and ER25yr160km. (a),(b) SSH amplitudes shown in logarithmic scale. Internal tides in shallow ocean (<1000 m) are discarded (blank). The black contours indicate regions of strong currents, where the satellite altimetric internal tides are noisy. Their global mean variances are calculated and given (excluding regions of strong currents). (c),(d) Model evaluation using the satellite altimetry data in 2020. Shown are variance reduction obtained by making internal tide correction. Their global mean variance reductions are calculated and given (excluding regions of strong currents). (e) Model variance difference of NR8yr160km minus ER25yr160km. (f) Variance reduction difference of NR8yr160km minus ER25yr160km.

NR8yr160km is a better internal tide model on global average, because it is constructed using data with a short time coverage, that is 8 years of data made by nonrepeat altimetry missions (2011–2018).

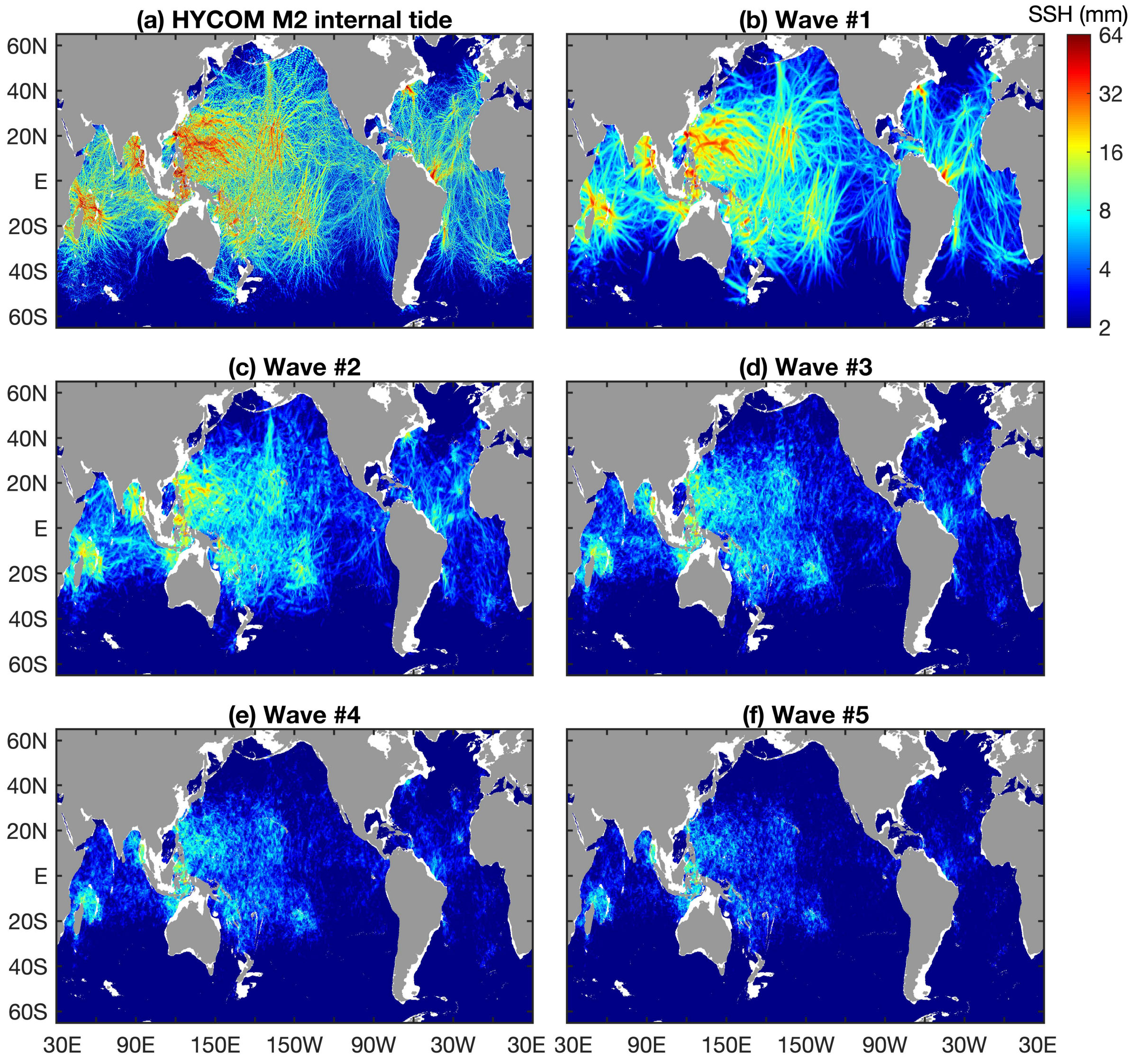
Internal tide energetics



The depth-integrated internal tide energy is calculated from the SSH amplitude. (a) NR8yr160km, (b) ER25yr160km, and (c) NR8yr160km minus ER25yr160km. The black contours indicate regions of strong currents, where the satellite altimetric internal tides are noisy. Their globally integrated energies (or differences) are calculated and given (excluding regions of strong currents). The global energies of NR8yr160km and ER25yr160km are 43.6 and 33.6 PJ, respectively, with a different of 10 PJ. NR8yr160km has higher energy than ER25yr160km, mainly because the former represents an 8-yr-coherent field while the latter a 25-yr-coherent field.

There are significant differences in (1) the internal tides from Amukta Pass, Alaska and (2) the internal tides from the Macquarie Ridge. There is another anomalous feature: NR8yr160km has slightly lower energy than ER25yr160km to the south of Hawaii. These features suggest that mode-1 M_2 internal tides are subject to strong interannual variability.

Decomposition of HYCOM simulations



Decomposition of the HYCOM simulated mode-1 M_2 internal tide field by plane wave analysis. The impact of window size on internal tide decomposition is examined using different fitting windows (40-, 60-, 80-, 100-, 120- and 160-km). Show here is an example using 100-km windows. After decomposition, long-range beams are clearly seen. The result confirms that internal tides are better represented by the 40-km fitting window employed in this mapping technique. It is expected that our satellite and HYCOM results will provide constraints on the incoherent internal tide, which is a function of time-series duration and location. In addition, the global internal tide dissipation map is computed using the new satellite observation, whose high resolution is a key improvement, because dissipation is derived from flux divergence. The satellite derived dissipation map compares well with that derived from the HYCOM simulation (under investigation).

Conclusions

Mode-1 M_2 internal tides have been estimated using 8 years of SSH measurements (2011–2018) made mainly by nonrepeat altimetry missions (phases). NR8yr has advantages over ER25yr in mapping internal tides, because NR8yr has dense ground tracks and short time coverage.

This work has been made possible by a new mapping technique, which consists of two rounds of plane wave analysis with a spatial bandpass filter in between. The new technique allows us to explore the spatiotemporal variability of internal tides.

The impact of window size is studied by taking advantage of the denser ground tracks of NR8yr. Mode-1 M_2 internal tides are mapped using six different fitting windows: 40-, 60-, 80-, 100-, 120-, and 160-km. On global average, the size of fitting window does not make much difference. However, small fitting windows can better resolve internal tides in isolated strong source regions. The small fitting windows are tested using the high-resolution HYCOM simulation.

The impact of time coverage is studied by comparing internal tide models NR8yr160km and ER25yr160km. NR8yr160km proves to be a better internal tide model, in that (1) it has larger model variance and (2) it reduces more variance in making internal tide correction to four sets of satellite altimetry data. It is because NR8yr160km represents an 8-yr coherent field, while ER25yr160km is a 25-yr coherent field.