Internal Tide Model ZHAO23: A Milestone Achieved by 30 Years of Satellite Altimetry Sea Surface Height Measurements from 1993 to 2022

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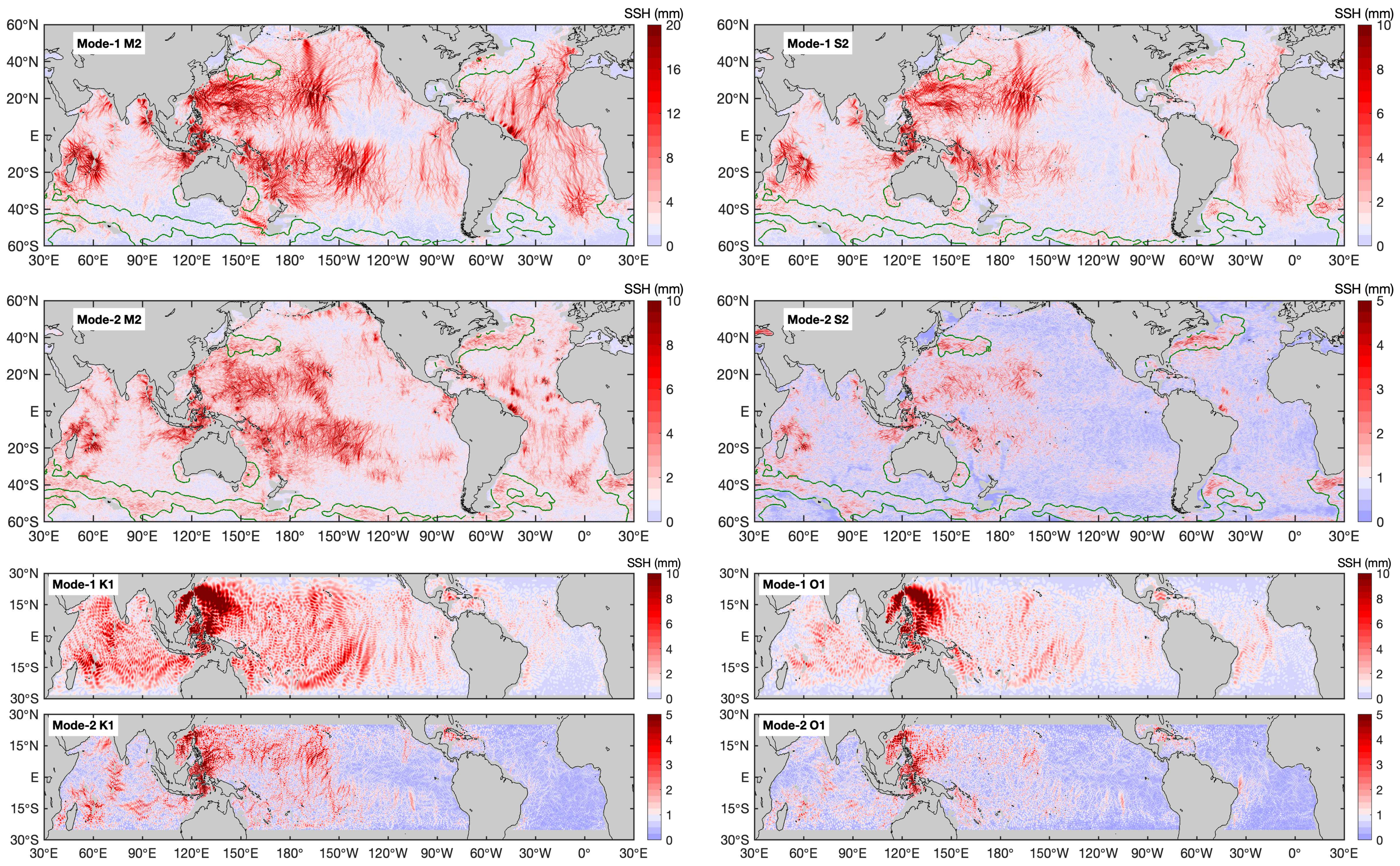
A new-generation internal tide model ZHAO23 is constructed using 30 years of sea surface height (SSH) measurements made by 15 satellite altimetry missions (excluding HY-2C and -2D) from 1993 to 2022. The merged data record is about 120 satellite years long. Our new mapping procedure consists of two rounds of plane wave analysis and a spatial bandpass filter in between. The mapping technique is developed utilizing the known frequencies and theoretical wavelengths of the target internal tidal constituents. Prior mesoscale correction is made using the spatiotemporally gridded SSH fields. ZHAO23 contains eight tidal constituents (M_2, S_2, N_2, K_2, O_1, K_1, P_1, Q_1) for the first baroclinic mode, four tidal constituents (M_2, S_2, O_1, K_1) for the second baroclinic mode, and one tidal constituent (M_2) for the third baroclinic mode. Model errors are objectively estimated using background internal tides that are mapped using slightly different tidal frequencies (periods ±3 min). The resulting model is evaluated using the satellite altimetry data in January–June 2023. The temporal variability of internal tides is studied using subsetted altimetry data following the same method. We find that internal tides are subject to significant variability on seasonal, interannual, and decadal timescales. The incoherence of internal tides due to seasonal and interannual variations can be quantified. In the past 30 years, the global mode-1 M_2 internal tides strengthened in terms of both SSH amplitude and depth-integrated energy, and their propagation speeds increased, although the internal tide strengthening is spatially inhomogeneous. The performance of empirical internal tide models in making internal tide correction is affected by internal tide strengthening.

❑ 30-year coherent components

We have constructed a new-generation internal tide model using 30 years of satellite altimetry data from 1993 to 2022. Prior mesoscale correction is made using AVISO gridded mesoscale fields (Ray and Byrne 2010). Our new mapping procedure consists of two rounds of plane wave analysis with a spatial bandpass filter in between. It is the latest mapping procedure over which we have been continuously improving since 2009. Meanwhile, we have carefully examined several empirical mapping parameters in the procedure. Theoretical wavelengths are computed from the WOA18 climatology. We have developed an objective method for estimating errors in our models using background internal tides, which are mapped using the same data following the same procedure, but for slightly different tidal periods (±3 min). The results show that our model errors are usually <1 mm in the global ocean and <0.5 mm in low-EKE regions.

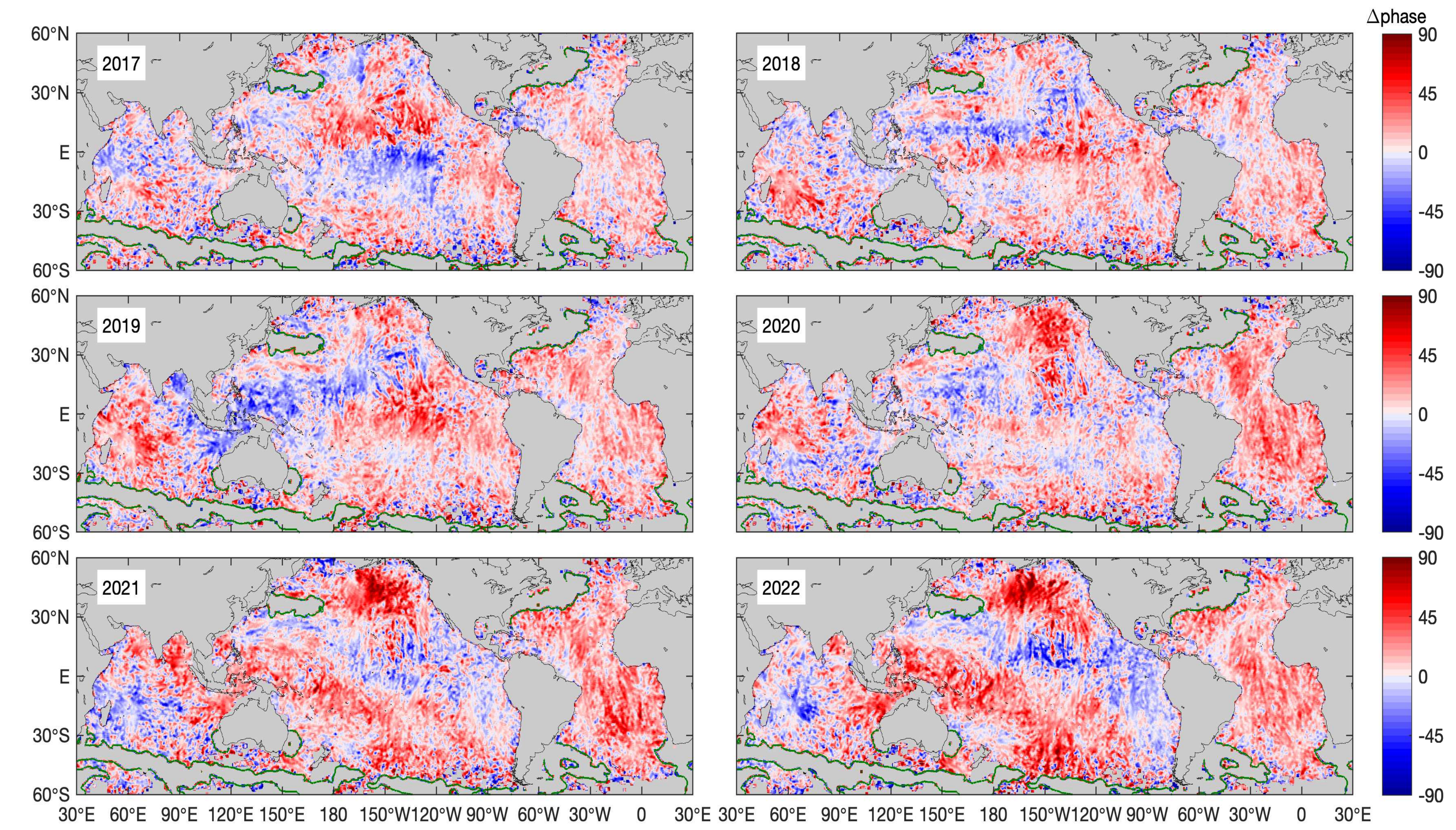
Our internal tide model contains 8 tidal constituents and totally 13 wave components. Shown below are the mode-1 and -2 M_2, S_2, K_1 and O_1 internal tides. The mode-1 N_2, K_2, P_1 and Q_1 internal tide cannot be shown due to poster limit. All of these constituents have been evaluated using independent altimetry data in 2023. ZHAO23 contains rich information on the generation, propagation, and dissipation of internal tides. More efforts are needed to examine the characteristics of the global internal tide field.



Zhao, Zhongxiang (2023). Mode-1 N_2 Internal Tides Observed by Satellite Altimetry. Ocean Science, 19, 1067–1082. https://doi.org/10.5194/os-19-1067-2023

❑ Incoherence due to interannual variability

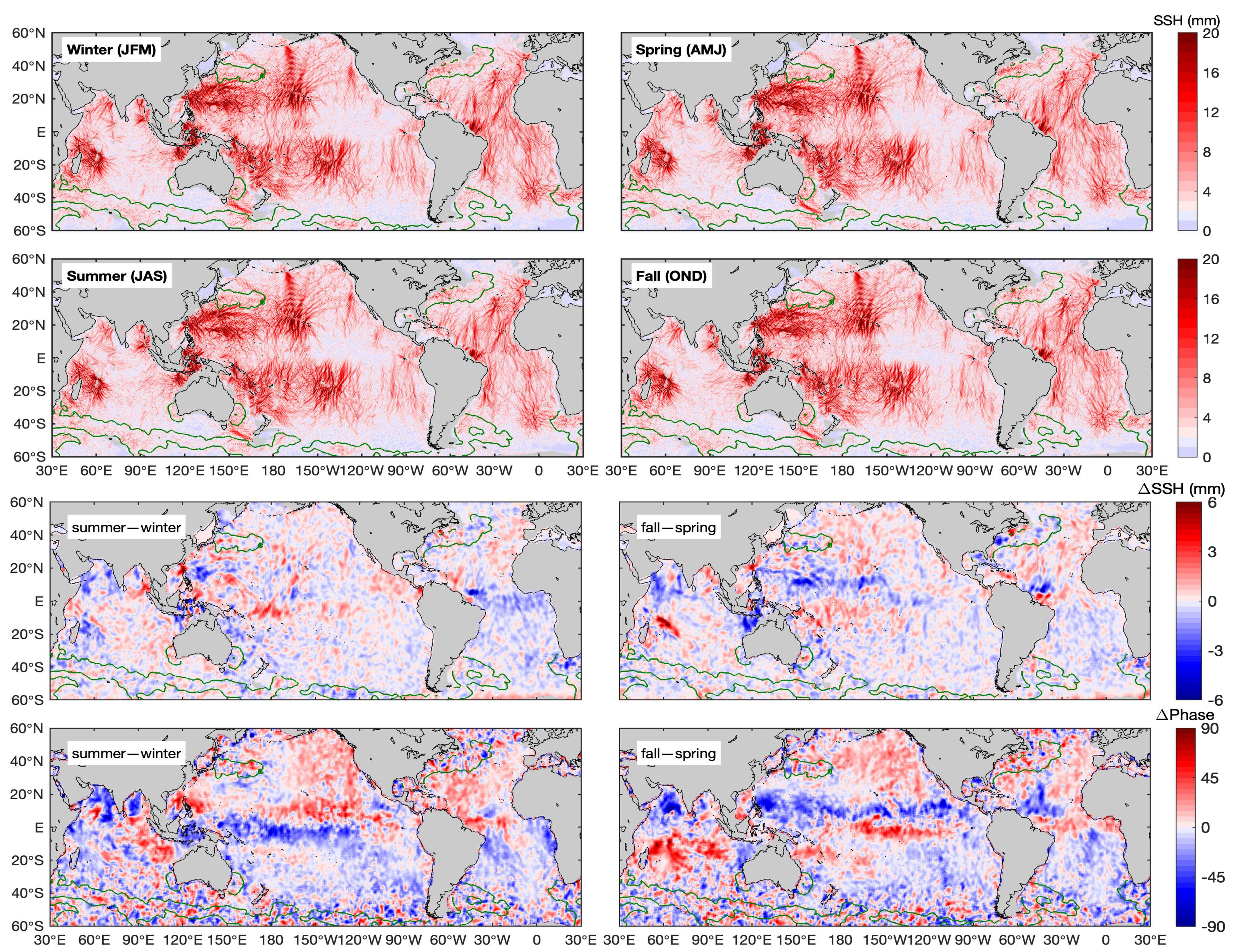
We have constructed 30 yearly mode-1 M_2 internal tide models using 30 yearly-subsetted satellite altimetry data from 1993 to 2022. The datasets range from 2 to 8 satellite years long. Thanks to our new mapping technique, the model errors are low particularly in recent years with 5 or more concurrent altimetry missions. Each model represents the one-year-coherent internal tide field. Their anomalies with respect to the 30-year-coherent model show that the mode-1 M_2 internal tides are subject to significant interannual variability in both amplitude and phase. The interannual variation is a function of location. The phase anomalies in 2017–2022 are shown below. We find clear large-scale features, as well as small-scale uncertainties. Note that the phase anomaly is mainly caused by the interannual variability of the phase speed of internal tides, which is caused by the interannual variability of ocean stratification. The figure demonstrates rich information on phase anomaly, which may be up to ±90 degrees. For example, in 2017, we find a negative region in the central South Pacific. In 2018, the negative region moves and lies along the equatorial Pacific. In 2019, the negative region shifts to the western North Pacific and eastern Indian Ocean. In 2020–2022, there exists a strong positive region in the Northeast Pacific. As a result, the interannual variation in phase leads to incoherent internal tides. The interannual variation must be taken into account in developing better and better internal tide models. In contrast, the interannual variation in internal tide amplitude is more challenging to quantify, because the relatively large errors may mask the signal. One might ask what is the yearly anomaly map in 2023, which we will examine next. It is important and time-consuming to extend this analysis to other tidal constituents.



Zhao, Zhongxiang (2022). Development of the Yearly Mode-1 M_2 Internal Tide Model in 2019. Journal of Atmospheric and Oceanic Technology, 39, 463–478. https://doi.org/10.1175/JTECH-D-21-0116.1

❑ Incoherence due to seasonal variability

We have constructed four seasonal mode-1 M_2 internal tide models using seasonally-subsetted satellite altimetry datasets from 1993 to 2022. Each dataset is thus 30 satellite years long. Mapping parameters are computed from the WOA18 seasonal hydrographic climatology. This analysis is made possible by our newly developed mapping procedure. Shown below are the four seasonal models. They are very similar without visual differences. However, the seasonal variations in amplitude and phase can be seen in their differences as shown below. The results show that mode-1 M_2 internal tides are subject to significant seasonal variability and that their seasonal variations are a function of location. Large seasonal variations predominantly occur in the tropical zone, where the WOA18 shows strong seasonal variations in ocean stratification. Seasonal phase variations are dominantly ±60° at the equator and up to ±120° in the central Arabian Sea. Incoherence caused by seasonal phase variations may be up to 50% in the tropical zone. The seasonally variable models are better in the tropical zone, where large seasonal signals may overcome model errors. Each seasonal model works best in its own season and worst in its opposite season. The performance of empirical internal tide model improves when the seasonal variability is taken into account.



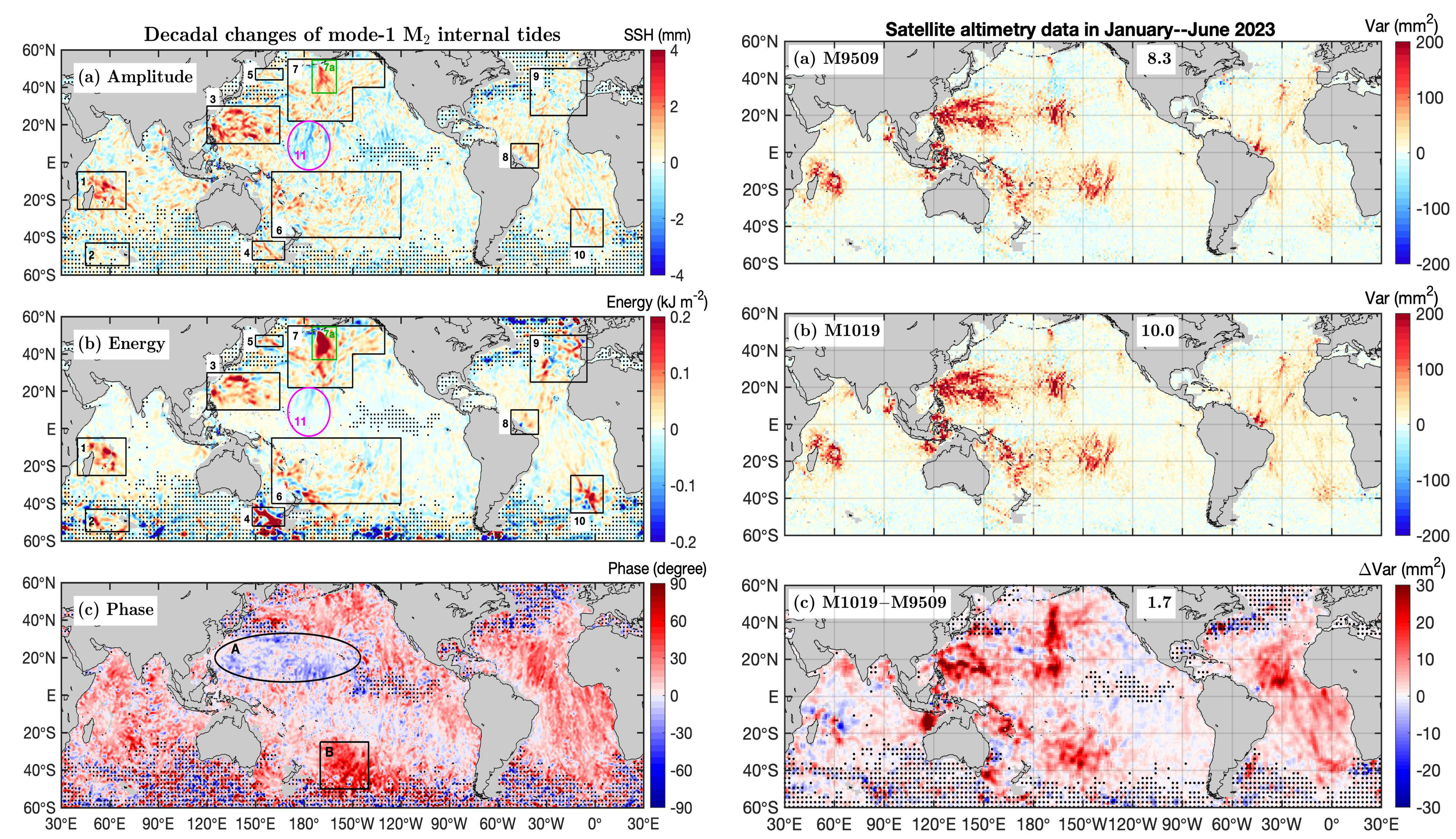
Zhao, Zhongxiang (2021). Seasonal Mode-1 M_2 Internal Tides from Satellite Altimetry. Journal of Physical Oceanography, 51, 3015–3035. https://doi.org/10.1175/JPO-D-21-0001.1

❑ Incoherence due to decadal strengthening

We have constructed two mode-1 M_2 internal tide models M9509 and M1019 using satellite altimetry datasets in 1995–2009 and 2010–2019, respectively. The two datasets each are about 48 satellite years long, such that the models have same and low errors. The 18.6-year lunar nodal cycle is corrected in our mapping procedure. To account for the decadal change in stratification, two sets of decadal hydrographic profiles in the WOA18 are used to provide parameters: 1995–2004 (95A4) and 2005–2017 (A5B7). On global average, the M_2 internal tides strengthened by 6% in energy over 12.5 years from March 2003 to August 2015 (centers of the two datasets). The changes will be 2.4 times larger assuming a constant rate over the 30 years. The internal tide strengthening is spatially inhomogeneous. M1019 leads M9509 by about 10 degrees (20 minutes in time), suggesting that the propagation speed of M_2 internal tides increased.

Strengthened M_2 internal tides are observed in the following regions: (1) the Madagascar-Mascarene region (25%), (2) the Conrad Rise and Kerguelen Plateau, (3) the western North Pacific (20%), (4) the Tasman Sea (15%), (5) the Kuril Strait, (6) the western South Pacific, (7) the central and eastern North Pacific (15%), (7a) the Aleutian Ridge (30%), (8) the Amazon continental region, (9) the Northeast Atlantic Ocean, and (10) the Walvis Ridge. Weakened internal tides are observed in central Pacific Ocean (11). Positive phase differences are observed throughout the Atlantic and Indian Oceans; however, negative phase differences are observed in regions such as the tropical North Pacific. The largest phase differences occur in the southern Pacific Ocean.

M9509 and M1019 are evaluated using independent altimetry data. The results show that M9509 and M1019 perform better for the data in 1993–1994 and 2020–2022, respectively. Shown below is for independent data in January–June 2023. The global mean variance reduction is calculated. M1019 performs better than M9509, because of the strengthened M_2 internal tides over the past 30 years. M1019 is constructed using altimetry data that are closer to the independent data in time. Internal tides are weaker than model errors in the dotted regions. A better internal tide model should take into consideration of internal tide strengthening (Zhao 2023 GRL).



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