Towards Realistic Nonstationarity of Semidiurnal Baroclinic Tides in a Hydrodynamic Model

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Key Points:

- Hydrodynamic models incorporating mesoscale dynamics and tides are beginning to resolve stationary and nonstationary baroclinic tides.
- The ratio of nonstationary to total semidiurnal variance computed from altimetry and a HyCOM simulation agree at low and middle latitudes.
- Comparisons of analysis methodologies show that the total and nonstationary semidiurnal variances are underestimated in altimetry on average.

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Abstract

Semidiurnal baroclinic tide sea surface height (SSH) variance and semidiurnal nonstationary variance fraction (SNVF) are compared between a hydrodynamic model and altimetry for the low- to mid-latitude global ocean. Tidal frequencies are aliased by the ∼10-day altimeter sampling, which makes it impossible to unambiguously identify nonstationary tidal signals from the observations. In order to better understand altimeter sampling artifacts, the model was analyzed using its native hourly outputs and by subsampling it in the same manner as altimeters. Different estimates of the semidiurnal nonstationary and total SSH variance are obtained with the model depending on whether they are identified in the frequency domain or wavenumber domain, and depending on the temporal sampling of the model output. Five sources of ambiguity in the interpretation of the altimetry are identified and briefly discussed. When the model and altimetry are analyzed in the same manner, they display qualitatively similar spatial patterns of semidiurnal baroclinic tides. The SNVF typically correlates above 80% at all latitudes between the different analysis methods, and above 60% between the model and altimetry. The choice of analysis methodology was found to have a profound effect on estimates of the semidiurnal baroclinic SSH variance with the wavenumber-domain methodology underestimating the semidiurnal nonstationary and total SSH variances by 68% and by 66% respectively. These results produce a SNVF estimate from altimetry that is biased low by a factor of 0.92. This bias is primarily a consequence of the ambiguity in the separation of tidal and mesoscale signals in the wavenumber domain.

1 Introduction

The identification and removal of the internal tide sea surface height (SSH) signal is a first-order problem in satellite altimetry. Compared to the relatively large-scale barotropic tides, baroclinic tides (also called internal tides) have a small SSH amplitude (order of cm), are spatially short (order of 100 km) and are significantly affected by ocean stratification and mesoscale currents, making them intrinsically difficult to both discern in altimetry observations and to predict with hydrodynamic models. However, the removal of baroclinic tides from altimetry is critical for distinguishing non-tidal phenomena, and ocean models are increasingly becoming an essential tool in this endeavor. The removal of internal tides will be especially important for the Surface Water and Ocean Topography (SWOT) wide-swath altimeter mission planned to launch in 2021 (Fu, Alsdorf, Morrow, Rodrigues, & Mognard, 2012), which will perform measurements at smaller length scales than any previous altimeter mission.

Currently, baroclinic tides are included in several models such as the Hybrid Coordinate Ocean Model (HyCOM) (B. Arbic et al., 2018; B. K. Arbic, Richman, Timko, Metzger, & Wallcraft, 2012; B. K. Arbic, Wallcraft, & Metzger, 2010), the MIT General Circulation Model (MITgcm) (e.g., Rocha, Chereskin, Gille, and Menemenlis (2016); Rocha, Gille, Chereskin, and Menemenlis (2016)), the German STORMTIDE model (e.g., Müller, Cherniawsky, Foreman, and von Storch (2012)), the Nucleus for European Modeling of the Ocean (NEMO) community model (Madec, 2008), and the Geophysical Fluid Dynamics Laboratory (GFDL) Generalized Ocean Layered Dynamics model (GOLD) (e.g., Waterhouse et al. (2014)). Some regional baroclinic tide models exist as well (e.g., Kelly, Lermusiaux, Duda, and Haley (2016)). In fact, it is only recently that computing power has progressed enough to feasibly allow global ocean models to run at the high spatial and temporal resolutions necessary to resolve baroclinic tides.

Baroclinic tides are created when barotropic tidal currents pass over sloping topography, generating internal waves that are phase-locked with the tidal forcing (Kelly, Nash, & Kunze, 2010). These phase-locked internal waves are referred to as stationary tides since they can be written in terms of a known amplitude and phase and are hence predictable. Internal tides may lose their phase relationship with the barotropic forcing as they interact with topography (e.g., Duda et al. (2012); Klymak et al. (2016)), as they propagate through time-variable ocean stratification (e.g., Buijsman et al. (2017)), or by interacting with sub-tidal flows including eddies and currents (e.g., Dunphy and Lamb (2014); Dunphy, Ponte, Klein, and Le Gentil (2017); Kelly and Lermusiaux (2016)). These are called nonstationary tides, and they are less predictable by nature. Hydrodynamic models that are able to simulate internal tides along with mesoscale and submesoscale dynamics should also simulate nonstationary internal tides, meaning it may be possible for them to aid in predicting nonstationary tides for future altimetry missions. Motivated by this, the percent variance of the semidiurnal (twice-daily) internal tides that is nonstationary in a hydrodynamic model will be computed in this paper and compared with the same quantity computed from altimetry.

Although their temporal resolution is relatively coarse, altimeter observations have been used to study global baroclinic tides (Ray & Mitchum, 1996, 1997; Ray & Zaron, 2016; Zhao, Alford, Girton, Rainville, & Simmons, 2016). With a temporal resolution on the order of 10 days, altimeters alias the tides and other high-frequency motions onto lower frequencies. To circumvent the issue of aliasing, tidal analyses using altimetry are often performed in the wavenumber domain. The differences caused by the choice of analysis in either the frequency or wavenumber domain has not yet been quantified in the context of ocean tides. In this work, we use both methodologies to analyze model output with a sufficiently high temporal resolution to investigate this quandary.

Several studies exist where altimeter observations are used to gauge the fidelity of global simulations containing baroclinic tides (Ansong et al., 2015; B. K. Arbic et al., 2012; Müller et al., 2012; Shriver et al., 2012), of which all but Müller et al. (2012) focused on HyCOM. These studies found that the spatial averages of stationary tidal amplitudes in HyCOM agreed well with observations in 'hot-spot' regions of large internal tide generation, but did not agree as well in regions of strong mesoscale activity and/or small tidal amplitudes (Shriver et al., 2012). This study goes one step further by comparing the nonstationary tidal amplitudes and semidiurnal nonstationarity variance fraction (SNVF) on basin- and global scales.

No matter if the analysis is done in the frequency or wavenumber domain, SNVF is determined by computing the spectra before and after the stationary tides have been subtracted from the time series, integrating over the semidiurnal internal tide frequency or wavenumber band, then computing the ratio of the nonstationary to total semidiurnal variance. This procedure for computing SNVF is relatively easy to perform in the frequency domain since the tides and other physical features (e.g. mesoscale eddies) have clearly separate time scales. However, in the wavenumber domain, internal tides and mesoscale eddies have similar length scales, and there is ambiguity in how to separate these signals. This leads to a number of subjective choices that will be identified and discussed. The model is sufficiently resolved to use both methodologies, allowing for the identification of limitations and biases in the wavenumber domain methodology. Implications of these limitations and biases for past and future altimetry missions will be briefly explored.

2 Data and Methods

The objective of this paper is to assess the nonstationary tides within a state-of-the-art ocean model by comparing them with data available from satellite altimetry. By definition, the nonstationary tide refers to a signal that originates from the tide generating force but is not phase-locked to this forcing. This definition corresponds most logically with an analysis method that first identifies the stationary tide by harmonic analysis – identifying the signal component that is phase-locked to the tidal forcing – and then identifies the residual signal within a given frequency bandwidth around the known tidal frequencies. Thus, the identification of the nonstationary tide is most naturally accomplished in the frequency domain. While it is feasible to analyze the tides in the hourly output of a numerical model using this methodology (Buijsman et al., 2017; Savage et al., 2017), which shall be referred to as the "f-space" (frequency-space) methodology, it is not feasible to apply this to altimeter data. Various approaches have been employed to identify nonstationary tides from altimetry, but ambiguity is introduced by the limitations inherent in the sampling of altimeters which alias the tidal frequencies (Zaron, 2015, 2017; Zhou, Wang, & Chen, 2015). The method used in this paper shall be referred to as the "k-space" (wavenumber-space) methodology, since it infers the nonstationary tide from the wavenumber spectrum, rather than the frequency spectrum.

In this section the k-space methodology that was originally used with altimetry is described in detail. The key to the comparison of model and data in this study is to use the k-space methodology on the model output, after subsampling to match the altimetry. Additionally, though, the native-resolution model output permits the separate comparison of the k-space and f-space methodologies, solely from model output, in order to identify likely errors and biases in the k-space approach – a comparison which is not possible from analysis of altimeter data alone.

2.1 Altimetry

The altimeter data and analysis methodologies used in this study come from Zaron (2017). The data consists of the combined 23 years of TOPEX/Poseidon, Jason-1, and Jason-2 (T/P-J) altimeter measurements with all standard corrections applied, including environmental path delays, the inverse barometer effect, sea-state bias, mean sea level, solid earth tides, and barotropic tides. From these data, 2,000 km long track segments centered at each ascending and descending track cross-over point were collected. For data near land, tracks shorter than 1,200 km or with gaps greater than 30 km were rejected.

The orbit repeat time of the T/P-J altimeters is 856712 seconds (9.91565 days) on average (Benada, 1997). Because of this, traditional f-space analyses cannot easily distinguish tidal motions in altimeter data since all sources of variability with frequencies shorter than half the altimeter sampling frequency will be aliased onto lower frequencies. This orbit repeat time was chosen so that tidal aliases would not overlap with significant periods of climate variability such as the seasonal cycle, annual cycle, or longer periods. Even so, tens or sometimes even hundreds of altimeter passes are needed to reliably separate tidal variability from other motions (see, for example, the tidal aliasing periods associated with the T/P-J missions in Table 3 of Ray (1998)). Therefore, the along-track analysis of internal tides from altimetry is typically performed in k-space. The k-space analysis method of Zaron (2017), which is based upon methods in Ray and Zaron (2011), will be summarized here.

First, an estimate of non-tidal variability was subtracted from the SSH anomaly relative to the record-length mean SSH to reduce the amount of non-tidal mesoscale variability. This "mesoscale correction" was performed by subtracting the SSH fields from the Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) center's Data Unification and Altimeter Combination System (DUACS) version DT-2014 (Pujol et al., 2016). This mesoscale correction was also used in Ray and Zaron (2016) and Zaron (2017), although it has been noted that there is some leakage of internal tide variability in this AVISO data (Zaron and Ray (2018); also see the Appendix of Ray and Zaron (2016)). Even with this contamination, this mesoscale correction was found to be essential for identifying internal tidal signals in the temporally-aliased altimeter data.

From this "corrected" data, the stationary tide was identified and removed from each time series using harmonic analysis. k-space power spectral densities were then computed along each track for each altimeter cycle from both the total and stationary tide-subtracted (or nonstationary) SSH data with Hann windows applied. These spectra were then averaged over all cycles. It should also be noted that, contrary to some previous works (e.g., Ray and Zaron (2016)), no high-pass spatial filter was applied to the along-track data at any point during this analysis. The high-pass filter used in these works was originally used to remove mesoscale eddies and other larger-scale features, but it was found to remove some tidal variability as well, hence our choice to neglect this operation.

In Zaron (2017), the SSH k-space spectra were shown to consist mainly of a broadband continuum besides a bump around the baroclinic wavenumbers and a white-noise-like spectrum at short wavelengths ($\leq$ 30 km). The noise level was defined by averaging the k-space spectra beyond this limit, and the broadband continuum was modeled as a low-order polynomial.

The variance associated with the mode-1 semidiurnal internal tides is estimated by integrating the variance under the spectral bump. The relatively short length of the along-track segments does not permit resolution of the wavenumber peaks associated with individual tidal frequencies in the semidiurnal band (e.g., M2, S2, N2, etc.); therefore, the integrated variance is a sum of all these components. Since the M2 tide is generally the largest amplitude, the wavelength of the mode-1 M2 tide, denoted k_{M2}, is used to locate the peak, and variance is computed by integrating between wavenumbers k_1 and k_2, $k_1 \leq k_{M2} \leq k_2$, defined by the local minima in the corrected spectrum closest to k_{M2}. The white-noise and broadband variances between these wavenumbers were also computed and subtracted, resulting in "residual" total and nonstationary variances. The semidiurnal nonstationary variance fraction (SNVF) was then computed by dividing the residual nonstationary variance by the residual total variance. See Figure 1 for an application of this methodology at a single altimeter cross-over.

The distinction between stationary and nonstationary variance is reasonably straightforward when time-resolved SSH is analyzed in the frequency domain (e.g., Colosi and Munk (2006)); however, the above-described methodology involves potentially problematic, and subjective, choices to deal with the altimeter temporal aliasing and relatively small signal-to-noise level. These choices include the definition of (1) the white-noise and (2) broadband spectra, (3) the mesoscale correction method, (4) the choice of integration limits, and (5) how the variance estimates from the ascending and descending tracks were reconciled into a single value. In order to reproduce the analysis of Zaron (2017), we had to replicate their choices as closely as possible; these choices will be discussed in the results. The five subjective choices used by Zaron (2017) were used when performing the k-space analyses of the model data, with one small difference; the mesoscale correction for the model was performed by subtracting the weekly-running mean from every time series, replicating a "perfect" implementation of the mesoscale correction methodology applied by Zaron (2017).

2.2 Model Output

This work uses 5 years of hourly steric SSH output from a HyCOM simulation managed by the Naval Research Laboratory (NRL) run on a tri-polar spatial grid with a nominal spacing of 1/12.5° near the equator. In addition to the standard atmospheric forcing fields, this simulation included forcing at the four strongest diurnal tides (K_1, O_1, P_1, Q_1) and the four strongest semidiurnal tides (K_2, M_2, N_2, S_2). Steric SSH instead of total SSH was used since it doesn't contain barotropic motions. See the appendix of Savage et al. (2017) for a discussion of the procedure used to compute steric SSH in HyCOM.

The output from this simulation was used in Shriver et al. (2012) and numerous studies thereafter (Richman, Arbic, Shriver, Metzger, & Wallcraft, 2012; Timko et al., 2012, 2013). There are newer HyCOM tides simulations having higher spatial resolution (e.g., 1/25° as in Savage et al. (2017)) and more accurate barotropic tides (e.g., Ngodok, Souopgui, Wallcraft, Richman, and Shriver (2016)), but the older simulation was used because of its longer output duration (5 years as opposed to 1 year in other simulations, including Savage et al. (2017)). The longer output was essential when analyzing the altimeter-sampled model output because altimeter sampling provides only about 72 tracks per cross-over point per year, and longer time series of SSH have been shown to produce better estimates of nonstationarity (Ansong et al., 2017).

Because the output of the HyCOM simulation was saved hourly, it is feasible to compute the tidal statistics using the f-space methodology, defined as integrating the frequency power spectral densities of the total and nonstationary SSH time series between 1.85-2.05 cycles per day (Savage et al., 2017) at the model grid point closest to the respective altimeter cross-over point. However, it is important to process and analyze the model output in the same fashion as the observations in order to obtain the most reasonable comparison between the two. In this case, the hourly model output was sampled using the spatial pattern of sampling along the T/P-J tracks (Benada, 1997). Additionally, having both hourly and altimeter-cycle time series allows us to compute the tidal statistics using three possible methodologies:

1. k-space of the altimeter tracks sampled once per altimeter cycle,
2. k-space of the hourly altimeter tracks, and
3. f-space of the hourly time series averaged over all altimeter points.

The first analysis is the best analogue to that used in the observations, so the results of this analysis are the best choice for comparing the model output to the observations. The second analysis will be used to investigate how the temporal sampling of the altimeters affect the k-space results. The last analysis will be used to investigate possible biases in using the k-space methodology in place of the f-space methodology when both methodologies are feasible.

3 Results

3.1 Analyses at a Single Location

To validate our analysis procedures, we applied them to altimeter-sampled HyCOM tracks corresponding to the six regional analyses defined in Section 4 of Zaron (2017). These locations have varying strengths of mesoscale variability, stationary tides, and nonstationary tides. For brevity, the results of only one test location will be shown here; the cross-over point located at 10°S, 3°W in the Southeast Atlantic. This location was chosen for this discussion since it contains moderate strengths of both tidal and non-tidal variability. The results of these analyses are displayed in Figure 1. The five subjective choices in the k-space methodology listed at the end of Section 2.1 will now be discussed:

1. Noise removal. Zaron (2017) and others have noted the presence of a pervasive white-noise spectrum that can be characterized using the high-wavenumber portion of the spectrum. For this work, the white-noise region was defined akin to Zaron (2017) at wavelengths lower than 30 km. Since this white-noise spectrum is subtracted from the full spectrum, the subjective choice of how to define the white-noise spectrum could affect the later variance estimates. The noise is generally much smaller than the variances of interest in the altimeter data and is almost non-existent in the model, so the results are the least sensitive to this choice amongst the five.

2. Broadband removal. The broadband spectrum differs greatly with location (see, e.g. Figure 2 of Zaron (2017)). Additionally, the mesoscale correction can significantly affect the shape of the broadband spectrum. This makes it tricky to choose a satisfactory global definition for the broadband spectrum. In this work, an order-2 polynomial was chosen to account for any curvature in the broadband while limiting any overfitting that could occur when using higher-order polynomials.

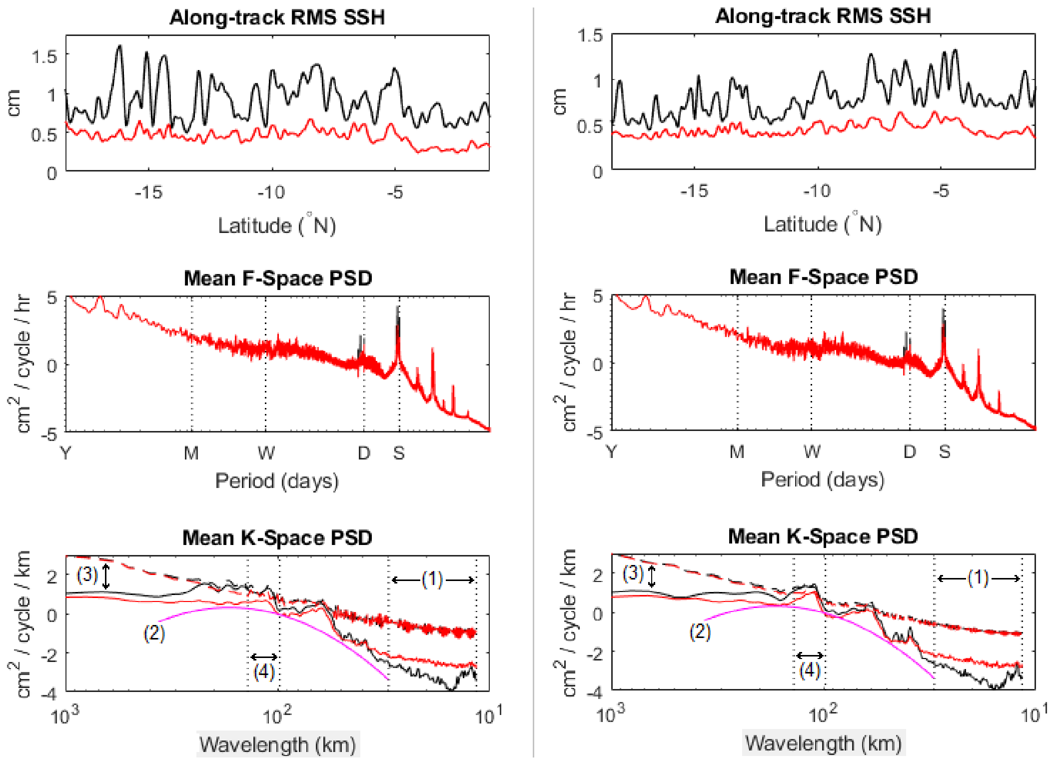

Figure 1. Along-track analysis of the altimeter-sampled HyCOM output from the Southeast Atlantic centered on 10°S, 3°W for the (left) ascending track and (right) descending track. (Top) Total (black) and nonstationary (red) semidiurnal root-mean-square SSH values at each point along each track. (Middle) Mean f-space power spectral density from each model output hourly time series along each track. Vertical dotted lines are plotted at yearly (Y), monthly (M), weekly (W), diurnal (D), and semidiurnal (D) frequencies. (Bottom) Mean k-space power spectral density from each altimeter-sampled track, including spectra for the total SSH (black), the nonstationary SSH (red), and the broadband model (magenta). The dashed lines are the spectra when the mesoscale / non-tidal variability is not removed. The four numbers/regions label the first four of the five subjective choices of the k-space analysis method listed in the text. The uncertainty of the stationary tidal fit causes the increase in variance in the low wavenumbers of the nonstationary SSH spectrum relative to the total SSH spectrum.

3. Mesoscale / non-tidal variability removal. The choice of mesoscale model to remove non-tidal variability from altimeter-sampled results is another complexity. As has been shown, even utilizing an imperfect mesoscale model is important in clearly identifying the stationary internal tides (e.g., Ray and Zaron (2016)). For the altimeter-sampled model output, a weekly-running-average was subtracted from all time series to mimic a "perfect" mesoscale model following the characteristics of the mesoscale model used in Zaron (2017).

4. Choice of integration limits. At many locations, the local stationary tide is a sum of propagating stationary tidal waves from multiple sources. If the tides propagate at a high angle relative to the altimeter track (see, e.g., Figure 6 in Ray and Zaron (2016)), there may be multiple peaks in the wavenumber spectrum that may or may not reside within the integration limits of the mode-1 wavenumber k_{M2}. For example, the bottom subplot in Figure 1 show multiple

peaks beyond 100 km in the total SSH spectrum but not the nonstationary SSH. This indicates that there are sources of nonstationary tides propagating at large angles relative to the altimeter track, which manifests as variance at wavelengths beyond the k_{M2} band as defined in this work. Following previous works, the integration limits were chosen to be the local minima surrounding only the peak in the wavenumber spectrum closest to k_{M2}, meaning the semidiurnal variances at some locations may be grossly underestimated.

5. Reconciling results from the two tracks. In this work, the variance estimates from the ascending track and descending track are averaged to give a single value for the variance at each cross-over point. As mentioned in the discussion of the choice of integration limits, the k-space spectrum from the descending track contains a majority of its stationary semidiurnal variance between the local minima surrounding the peak nearest the k_{M2} peak, while ascending track k-space spectrum contains a significant amount of variance outside the k_{M2} integration limit at longer wavelengths. Since the variance estimates from the two tracks are averaged, the missing variance in the ascending track's variance estimate constitutes an as-of-yet unresolved error in the concluding variance estimate at this cross-over location.

3.2 Semidiurnal Variances and Variance Ratios

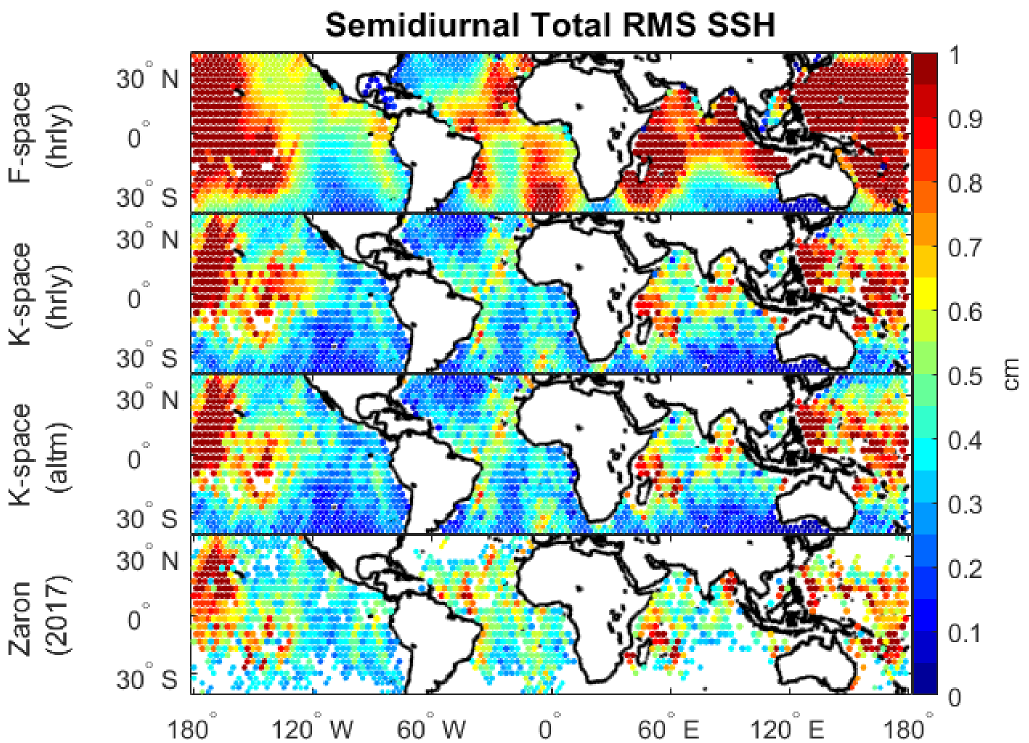

Figure 2. Global maps of semidiurnal total SSH variability (root-mean-square anomaly). The top three maps are computed from the HyCOM 1/12.5° 5-year run using (top) f-space methodology applied to the hourly output, (second) k-space methodology applied to the hourly output, and (third) k-space methodology applied to the altimeter-sampled output. These are plotted alongside (bottom) the results from altimetry in Zaron (2017). In all subplots, results are only plotted where the id=EDZtotal semidiurnal variance σ_T^2 is greater than twice the error variance σ_E^2.

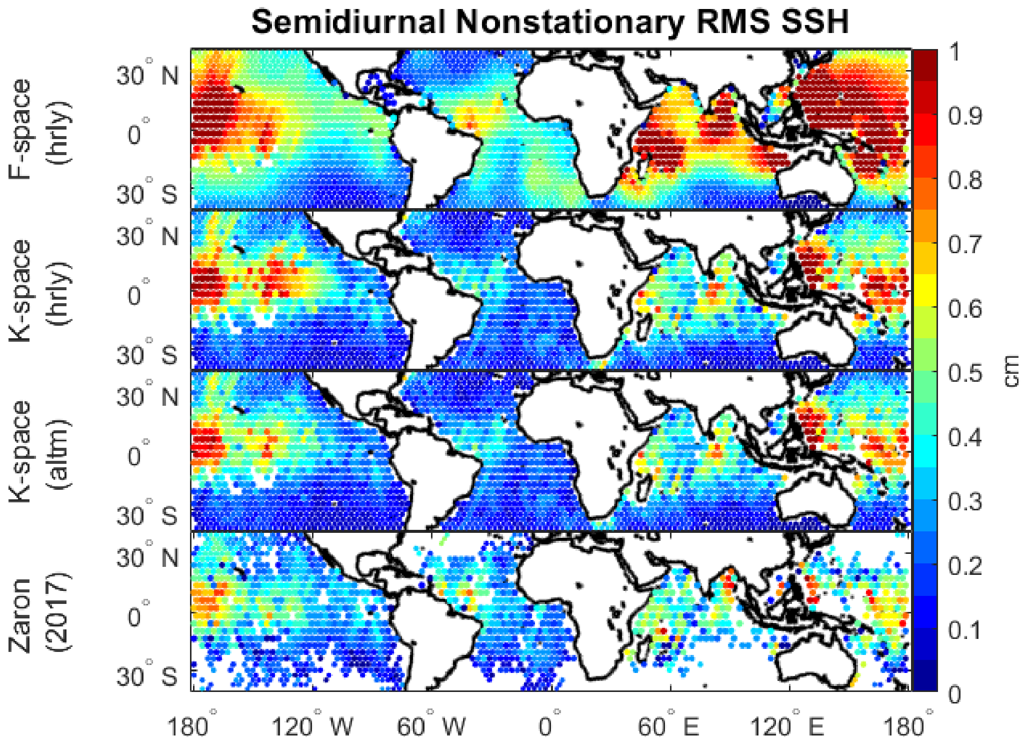

Figure 3. As in Figure 2, but for semidiurnal nonstationary SSH variability.

Figures 2 to 4 display global maps of the total and nonstationary semidiurnal-band SSH variabilities and SNVF for the three different methodologies listed in Section 2.2 along with the results from altimetry in Zaron (2017). At a cursory glance, all analyses show similar qualitative features. In the maps of nonstationary semidiurnal SSH variability (Figure 3), there is a large band of nonstationarity in the equatorial Pacific Ocean, due to the equatorial crossings of the stationary tides generated near Hawaii, near the Philippines, and in the tropical south and southwest Pacific. This is consistent with the analysis of the HyCOM simulation studied by Buijsman et al. (2017). There is additionally a large amount of nonstationarity in the Indian Ocean where the stationary tides generated near Madagascar cross the Mascarene Plateau, the Chagos-Laccadive Ridge, and the Ninety East Ridge as they propagate further eastward. There is also strong nonstationarity in regions of high mesoscale variability (e.g. boundary currents), where the mesoscale dynamical features (e.g. eddies) refract and scatter the internal tide. Additionally, as also found in Zaron (2017), low semidiurnal tidal variances and high observational uncertainties polewards of 40° caused the analysis to be restricted to equatorwards of 40°. In all figures, data are only plotted where the [id=EDZ]total semidiurnal variance σ_T^2 is greater than twice the error variance σ_E^2error variance σ_E^2 is less than twice the total semidiurnal variance σ_T^2. In the model, this error is almost zero.

The major discrepancy in these results is that the k-space method tends to underestimate both nonstationary and total semidiurnal variances. Conversely, the k-space method differs marginally when applied to 10-day sampled model output versus the original hourly output of the model, which is unsurprising as the altimeter repeat time was chosen specifically to minimize the temporal aliasing on the tides, and a three-year span was found to be satisfactory for capturing semidiurnal stationary tides (Ray & Zaron, 2011). The discrepancy in the f-space and k-space results stems from a combination of the five subjective parameters in the k-space method listed previously, the effects of which vary strongly with location. The ratio global area-weighted average

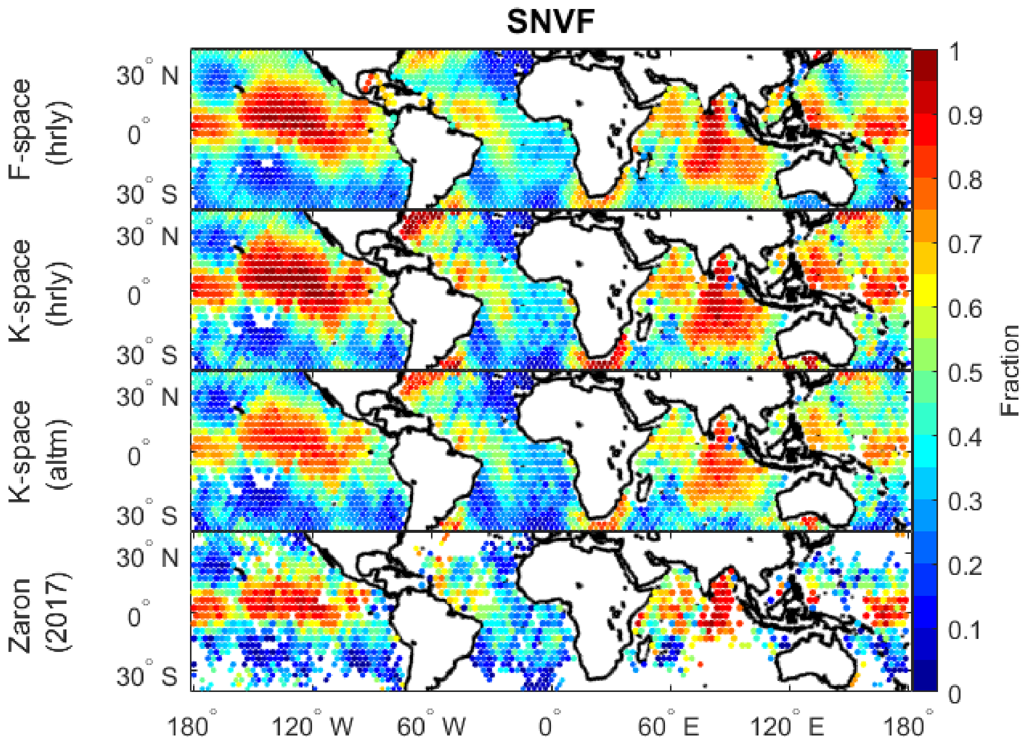

Figure 4. As in Figure 2, but for SNVF.

of the nonstationary semidiurnal variance from the k-space methodology (0.12 cm^2) versus that from the f-space methodology (0.37 cm^2) is 0.32. For the total semidiurnal variance, the ratio of the k-space estimate (0.26 cm^2) to the f-space estimate (0.77 cm^2) is 0.34. This highlights the importance of processing and analyzing observational data and model outputs as similarly as possible for the comparisons between the two to be meaningful. If the f-space methodology applied to the hourly data (e.g. this work, or the results of Savage et al. (2017)) were compared directly to altimetry, the model would appear to be grossly overestimating semidiurnal baroclinic variances, especially in the Indian Ocean and central and western Pacific Ocean. However, the k-space method applied to the altimeter-sampled model output agrees much better with the altimetry, showing more similar spatial patterns and variance magnitudes, with the model only slightly overestimating the semidiurnal baroclinic variances.

Perhaps most surprising is the similarities in the SNVF across analysis methods. Qualitatively, all three methodologies applied to the model output show very similar spatial patterns and SNVF values, all of which also appear to agree well with the results from altimetry. This robustness in the comparison of the variance ratios versus the individual variances was quantitatively assessed by computing the correlations between the various variances and SNVF across the different methods in 10° latitude bins. These correlations are displayed in Figure 5. All correlations are statistically significant to at least 95% confidence. Across all three comparisons, the SNVF has the highest correlation between analysis methods averaged across all latitudes. For all analysis methods and correlations from the model output, there is no discernible pattern versus latitude.

Between the model output and altimetry, the semidiurnal total SSH variance is consistently correlated versus latitude at 0.5-0.6 in the equatorial ocean and at 0.7-0.8 in the northern midlatitude ocean. Semidiurnal nonstationary SSH variance correlates most well along the equator and lessens as latitude increases polewards. This is due

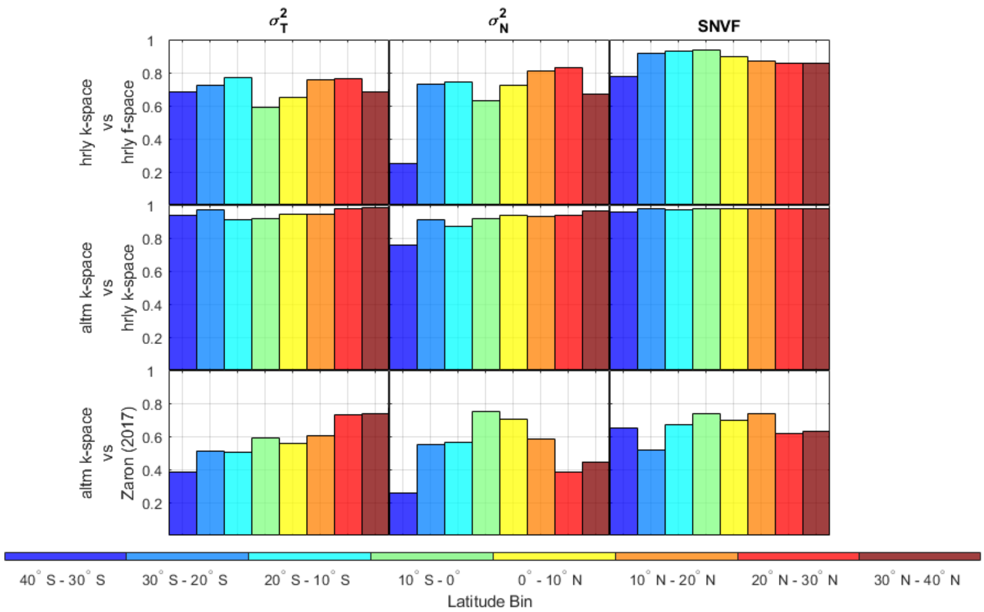

Figure 5. Correlations between the estimates of the semidiurnal variances of the total σ_T^2 and nonstationary σ_N^2 SSH and their ratio, the SNVF, between the three methodologies over 10° latitude bins.

to how the nonstationary tides are generated in these two regimes. Stationary tides propagating across the equator are mainly scattered by the change in ocean stratification and equatorial currents (Buijsman et al., 2017), which are relatively broad-scale and thus well simulated in the model. At higher latitudes, nonstationary tides are primarily generated by dynamical features such as eddies and western boundary currents. The HyCOM simulation did not include data assimilation, so the locations of these features, and thus the spatial distribution of the nonstationarity, may be mismatched relative to what was seen in altimetry. Surprisingly, even with these discrepancies in the stationary and nonstationary variances, the SNVF ratio stays relatively consistent across latitudes, although the correlations are slightly higher near the equator.

4 Discussion

As global ocean models such as HyCOM have attained progressively more realism through improved resolution and representation of atmospheric and tidal forcing, the related tasks of calibration and validation have proceeded step-wise, through model-data intercomparison of separate physical phenomena such as mesoscale kinetic energy (Thoppil, Richman, & Hogan, 2011), mesoscale available potential energy (Luecke et al., 2017), tidal SSH variability (Ansong et al., 2015; Shriver et al., 2012) and others. In this paper, we seek to validate a model's nonstationary tide, which arises as a joint phenomenon of the tides and mesoscale dynamics simultaneously. The motivation for this study is both to understand whether the model's representation of the interaction between these phenomena is adequate, and to establish a benchmark of skill for comparison of future efforts which will likely seek to forecast the nonstationary tide in the context of the SWOT swath altimeter mission (Fu et al., 2012).

A key finding of the present study is the degree to which the wavenumber-space (k-space) methodology underestimates the nonstationary tidal SSH variance. Assuming the model is accurate enough to be used as a guide, a comparison of the f-space and k-space methodologies finds that the latter is biased low and misses a large fraction of the nonstationary variance (cf., top two panels of Fig. 3). The k-space methodology was developed to overcome the effects of altimeter aliasing, but its implementation relies on several procedures, the validity of which cannot be tested from altimeter data alone. These procedures include (in order from least to most significant) the estimation and removal of a white-noise instrumental error spectrum, correction for the mesoscale/non-tidal SSH variability, estimation and removal of a broadband mesoscale/non-tidal spectrum, choice of integration limits defining the nonstationary spectrum bandwidth, and accounting for non-isotropy by averaging spectra from ascending and descending tracks. Zaron (2017) highlighted the role played by the assumed broadband mesoscale/non-tidal spectrum and noted that if this broadband spectrum consisted of a steeply sloped spectrum, e.g., k^{-3}, buried "underneath" the tide-dominated spectrum, then the nonstationary variance could be much larger than the values inferred there. Indeed, the present study indicates that this is the case. The ratio of the area-weighted global average of the semidiurnal nonstationary variance obtained with the k-space analysis (0.12 cm^2) with the f-space analysis (0.37 cm^2) is found to be 0.32. For the semidiurnal total variance, ratio of the variance from the k-space analysis (0.26 cm^2) to the f-space analysis (0.77 cm^2) is 0.34. However, the ratio of the area-weighted global average SNVF from the k-space analysis (0.45) to that from the f-space analysis (0.49) is 0.92.

Because the k-space analysis produces biased estimates of both the nonstationary and the total tidal variance, their ratio, the SNVF, is relatively well-correlated between the model and the altimetry (cf., Fig. 5). This positive correlation, and the map of Figure 4, suggest that HyCOM is accurately representing the interactions of the baroclinic tides and mesoscales; however, as the preceding paragraph makes clear, the altimeter data provide relatively weak constraints for describing the nonstationary tide — at least using the data and methods presently in the literature. The challenge with validating a global model such as HyCOM is the tradeoff between temporal- and spatial-resolution inherent in most data sources. Analysis of stationary and nonstationary tides using data from surface drifters is currently being investigated to overcome some of the limitations of altimetry data (Elipot et al., 2016).

5 Summary

In order to compare and validate ocean models results with observed data, it is necessary to implement ocean model analysis procedures that match the procedures used in the observations. This matched approach has been taken on in order to compare the nonstationary tides simulated with a combined tides-and-mesoscale-resolving HyCOM simulation with the nonstationary tides inferred using satellite altimetry. The comparison finds that the steric height variance associated with baroclinic tides is considerably larger in the model than in the data; however, the ratio of nonstationary to total tidal variance, denoted SNVF, is spatially-correlated between the model and data.

These results were rationalized by examining carefully the statistics of the nonstationary tide in different sub-samples of the model output, as they were progressively degraded from the native resolution of the model to the coarser resolution resolution of the altimetry. The notion of nonstationary tidal variance, which is unambiguously defined in the frequency domain, is not clearly defined in the wavenumber domain, and complicates the analysis of altimetry data. Assuming the HyCOM results are accurate enough to be used as a guide, the globally-averaged altimeter-based estimates of the nonstationary and total semidiurnal variances are only 0.32 and 0.34 of their true values, respectively. In other words, the altimeter underestimates the magnitude of the nonstationary and total semidiurnal variances by 68% and 66% respectively on average. Additionally, the SNVF is biased low by a factor of 0.92.

The spatial correlation of nonstationary tidal variance in the model with that inferred from altimetry suggests that the model is capturing a significant part of the interaction between baroclinic tides and the mesoscale circulation. A more comprehensive evaluation of the nonstationary tides in HyCOM is challenged by the lack of global data sets with the temporal resolution and duration necessary to resolve tidal variability. Future validation efforts might consider comparison of the rates of water mass transformation and mixing driven by the dissipation of the internal tide. Although this is a higher order quantity further removed from the tidal forcing and air-sea exchange, the integrative nature of water mass properties might make them straightforward to compare between model output and in-situ data.

Acronyms

HyCOM HYbrid Coordinate Ocean Model
MITgcm Massachusetts Institute of Technology general circulation model
GFDL Geophysical Fluid Dynamics Laboratory
GOLD Generalized Ocean Layered Dynamics
SWOT Surface Water and Ocean Topography
SSH sea surface height
SNVF semidiurnal nonstationary variance fraction

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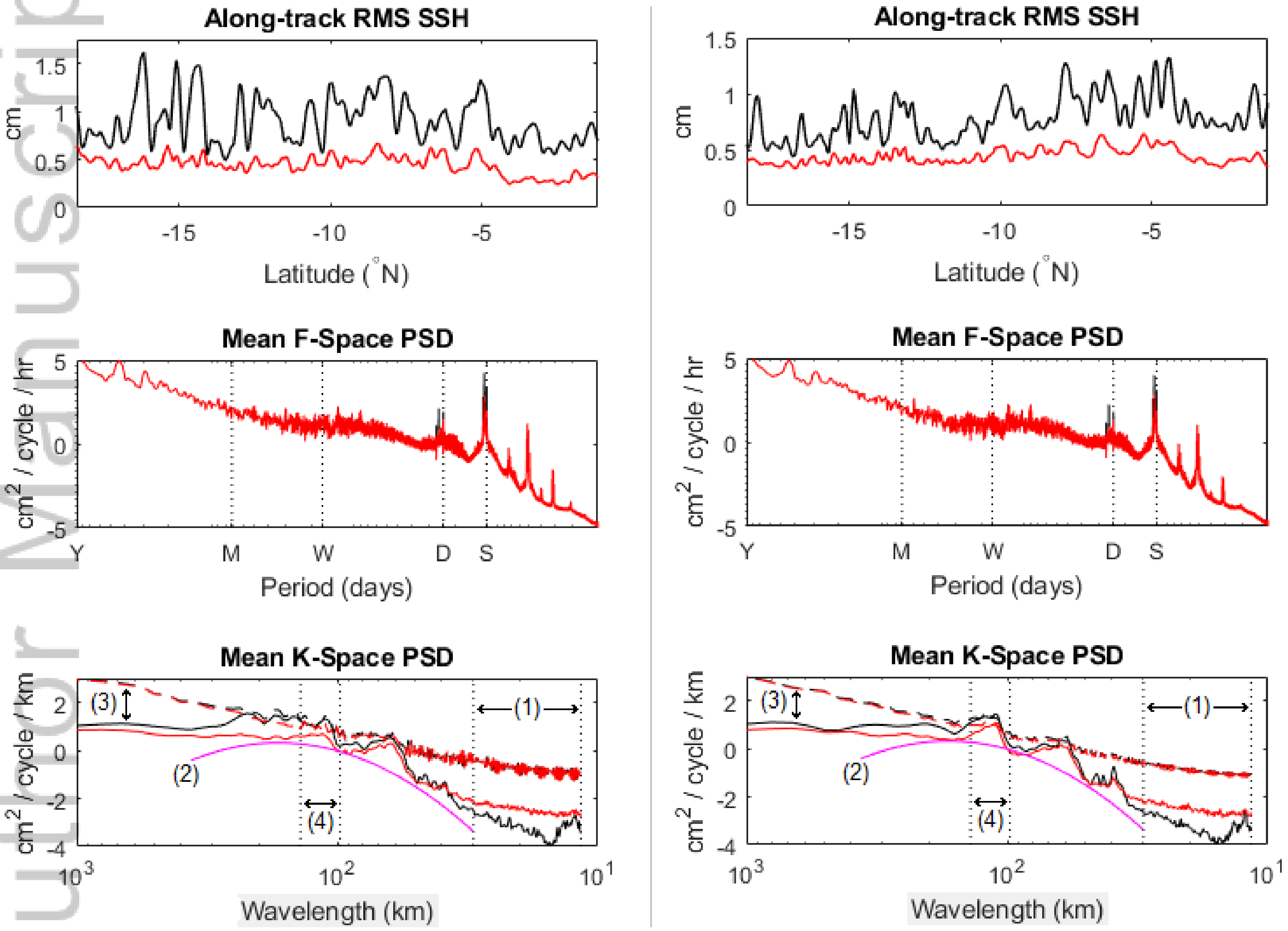

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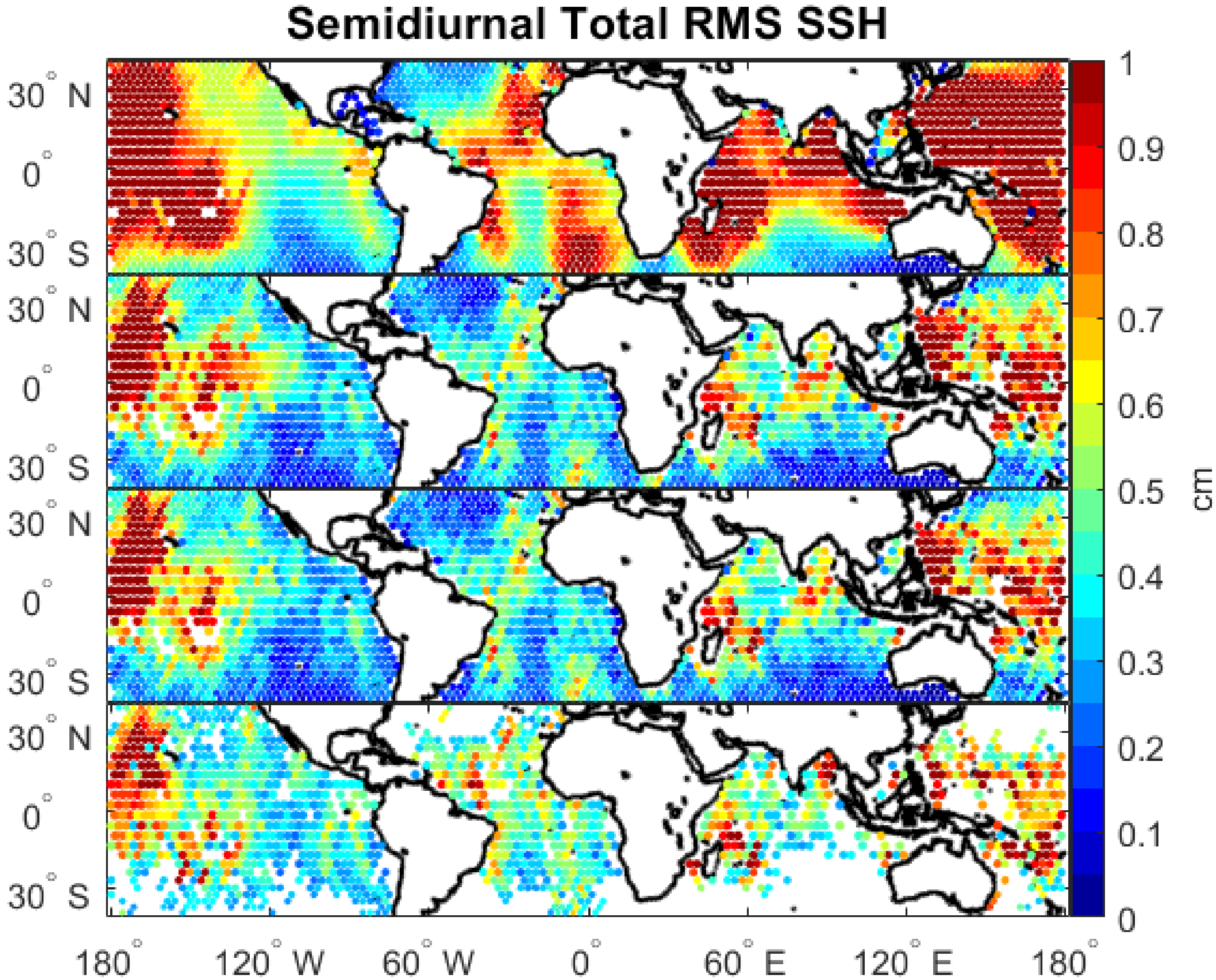

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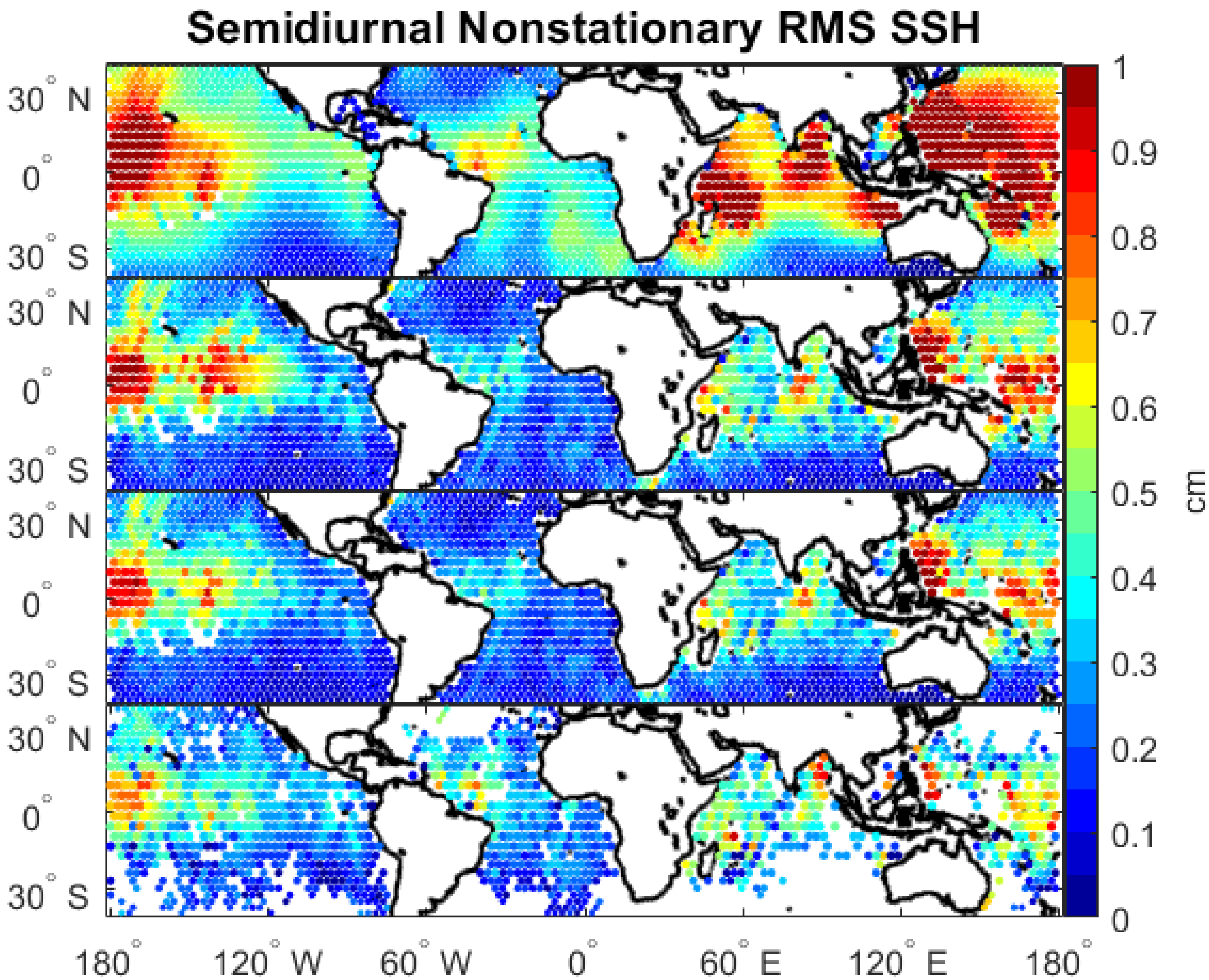

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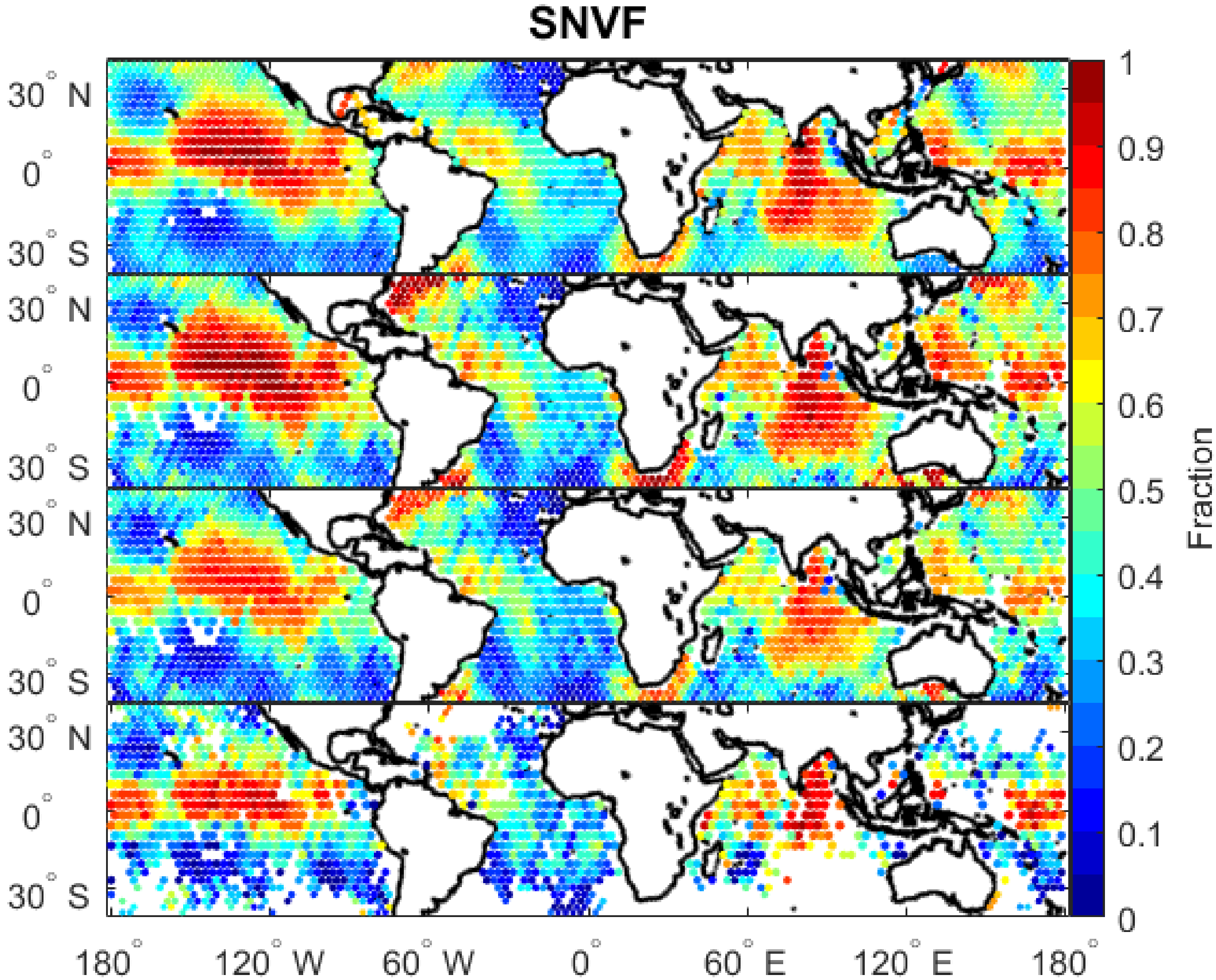

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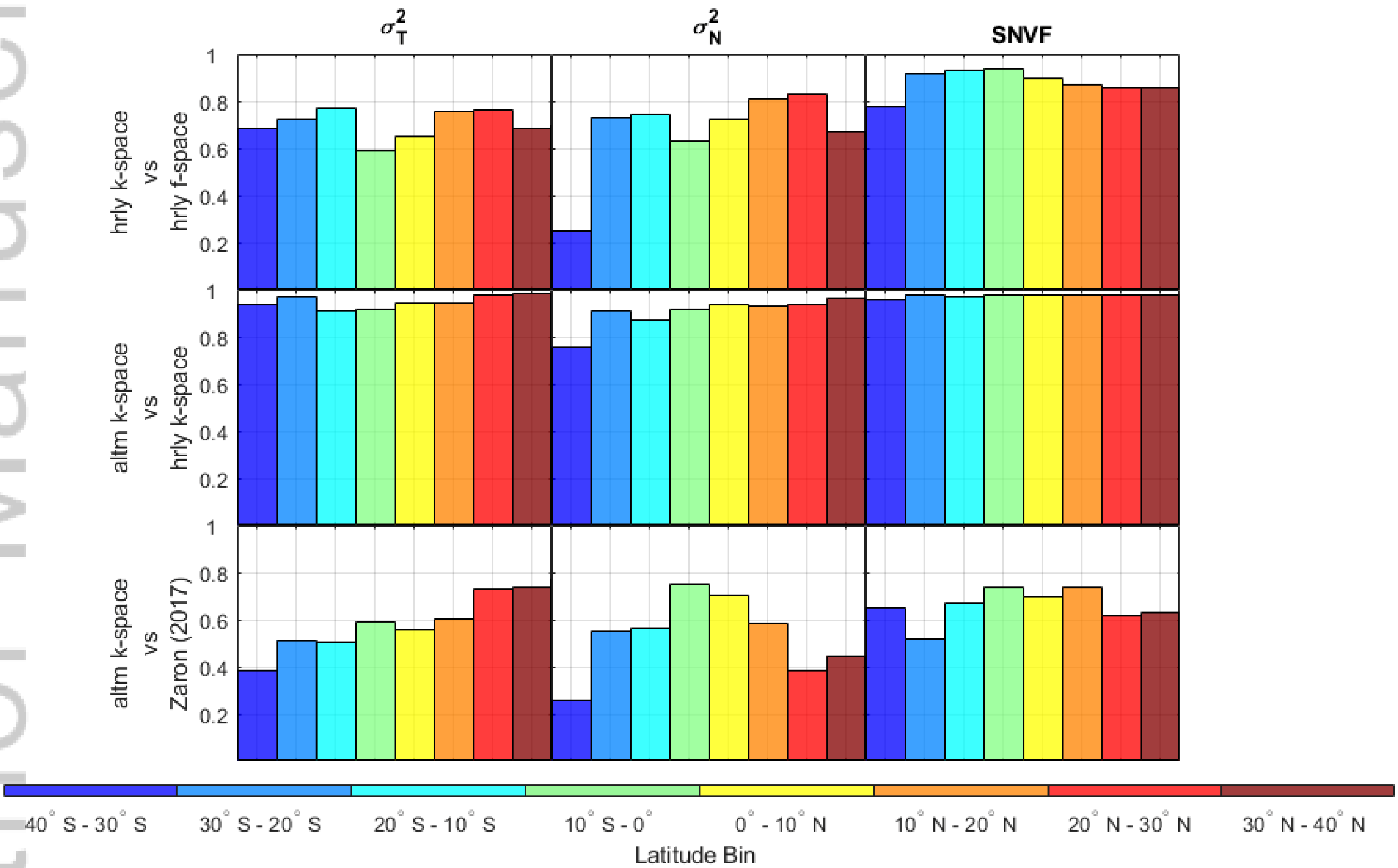

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