On the Long-Wavelength Validation of the SWOT KaRIn Measurement

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ABSTRACT

The Surface Water and Ocean Topography (SWOT) mission will measure the sea surface height (SSH) using a Ka-band radar interferometer (KaRIn) over a swath off the nadir of the satellite tracks. The mission requires calibration and validation (CalVal) of the SSH wavenumber spectrum at wavelengths between 15 and 1000 km. The CalVal in the short-wavelength range (15–150 km) requires in situ observations. In the long-wavelength range (150–1000 km), the CalVal will use the onboard Jason-class nadir altimeter. Using a high-resolution global ocean simulation, this study identifies the spatial scales beyond which the nadir and off-nadir observations can be considered comparable. Our results suggest that the ocean signals at nadir can represent off-nadir ocean signals at wavelengths longer than 120 and 70 km along the midswath and the inner edge of the KaRIn grid, respectively, indicating that the nadir altimeter is able to fulfill its goal to validate the long-wavelength KaRIn measurement. The wavelength along the inner edge is limited around 70 km because the onboard nadir altimeter cannot resolve spatial scales longer than ~ 70 km. These wavelengths provide a reference point for the required spatial coverage of the SWOT SSH in situ CalVal.

1. Introduction

The Surface Water and Ocean Topography (SWOT) is a new satellite mission highlighted in the 2007 decadal survey as the next-generation radar altimeter following the success of the decades-long nadir-looking altimeter (Durand et al. 2010). The main thrusts of SWOT for oceanography are the reduced instrument noise and the wide-swath measurements by the new Ka-band radar interferometer (KaRIn) in contrast to the measurements by conventional nadir-looking altimeters (Fu and Ubelmann 2014, hereinafter FU14). As always the case for a new mission, the validation of the new measurements is crucially important for understanding the instrument performance and the satellite measurements before any scientific application. SWOT aims to resolve the sea surface height (SSH) nominally down to 15-km wavelength. The measurement validation was required for 15–1000-km wavelengths and separated in short- and long-wavelength components. The short-wavelength (15–150 km) validation requires an in situ observational network (Wang et al. 2018). The long-wavelength (>150 km) validation will be performed by comparison with the nadir-looking altimeter as the truth (FU14).

Such validation is particularly important for assessing mission consistency in extending the existing decades-long altimeter measurements into future with the SWOT type of missions. Therefore, SWOT will carry a Jason-class nadir-looking altimeter, which is designed to validate the SWOT KaRIn measurements over long wavelengths (FU14).

However, the specific wavelength at which the nadir altimeter can be used for the SWOT validation (hereinafter nadir scale) has not been thoroughly evaluated. Wang et al. (2018) used a value of 150 km based on an analysis of the California Current region in a global numerical simulation. The global statistics on nadir scale remain unclear but are important for the mission's calibration and validation (CalVal). The spatial scale of the in situ CalVal field campaign may not need to cover 150-km distance if the nadir scale is generally shorter than 150 km.

Although the onboard nadir altimeter is useful in providing simultaneous observations, two factors limit its utility in the SWOT validation: 1) the higher instrument noise in the nadir altimeter limits its spatial resolution to be about 70 km and longer (Dufau et al. 2016), and 2) the SSH signal along nadir ground track will be different from the SSH over the SWOT swath which is at least 10 km away from nadir. For the former, the nadir

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FIG. 1. An example of the SWOT SSH swaths near the California CalVal site. The color shows the SSH anomaly after removing the along-track linear trend. The center line is the nadir altimeter SSH. There are two KaRIn swaths. Each swath is 50 km wide and 10 km off nadir.

altimeter cannot validate SWOT measurement below 70 km. For the latter, it is a question of at what wavelength the ocean signals at nadir are comparable to those off nadir because KaRIn measurements are 10–60 km away from nadir (Fig. 1). This is the main objective of this study, namely, to make a quantitative assessment of the wavelengths (nadir scale) longer than which the onboard nadir altimeter can be used as a validation reference. No existing observational database is available for the proposed quantitative assessment. To make progress, here we use a high-resolution global ocean numerical simulation for the quantification, which is described in section 2. Section 3 presents the main results. The conclusions and discussion are in section 4.

2. Method

a. The global ocean numerical simulation

Because of the lack of observations for the purpose of this study, we use a realistic numerical simulation for inference. The numerical simulation used in this study is the $1/48^\circ$ MITgcm global ocean simulation (referred to as llc4320) with tides and sea ice. This model and its performance have been documented in several recent studies (Rocha et al. 2016a,b; Wang et al. 2018; Savage et al. 2017; Su et al. 2018; Qiu et al. 2018;

Arbic et al. 2018; Wang et al. 2019). Only a brief description is included here.

The simulation domain spans the entire global ocean including sea ice. The model has been progressively spun up from its predecessors from the $1/6^\circ$ ECCO, phase 2 (ECCO2), state estimate, to $1/12^\circ$, $1/24^\circ$, and the final $1/48^\circ$ horizontal resolution (D. Menemenlis 2015, personal communication). There are 90 vertical levels with about 1-m resolution near the surface and ~ 300 m near the bottom. The surface forcing is derived from the 0.14° ECMWF reanalysis using the bulk formulas by Large and Yeager (2009). The barotropic tidal forcing is simulated using an additional pressure field applied at the sea surface. Energetic internal tides and internal gravity waves are well reproduced to match the observations in the region of interest (M. Mazloff et al. 2019, unpublished manuscript). A 1-yr simulation has been created with hourly output.

This simulation has been evaluated against observations by several studies. It has been compared with the upper-ocean ADCP measurements in the Drake Passage (Rocha et al. 2016a) and western Pacific Ocean (Qiu et al. 2018; Wang et al. 2018), satellite SSH (Qiu et al. 2018; Rocha et al. 2016b), and mooring measurements (C. Wunsch 2015, unpublished manuscript; Savage et al. 2017; M. Mazloff et al. 2019, unpublished manuscript). These studies show good agreement in terms of the velocity

structure of the general ocean circulation in the western Pacific and high-frequency internal gravity waves. Despite the stronger-than-observed tidal motions (C. Wunsch 2015, unpublished manuscript; Savage et al. 2017), the deviation from reality is not significant. Thus, we use the model to make a first attempt at identifying the nadir scale and provide a guideline, but the results will be revisited after the SWOT launch in 2021.

b. Synthetic SWOT measurements

To evaluate the nadir scale, we first create a set of synthetic SWOT measurements by applying the SWOT SSH simulator (Gaultier et al. 2016) to the global SSH field from llc4320. SWOT measures SSH with two 50-km-wide swaths separated by a 20-km gap along the nadir track (Fig. 1). The SWOT SSH simulator creates the latitude–longitude coordinates of the SWOT swaths and the nadir track according to the science orbit with a 21-day cycle and 78° inclination. The SWOT swaths cover the whole global ocean except for the Arctic between 78°N and 78°S. The global SSH field in the numerical simulation is then interpolated onto the SWOT swaths to produce synthetic SWOT measurements. We do not explicitly consider SWOT noise and error, which are not of concern at long wavelengths, but focus on the ocean signal itself. Figure 1 shows a segment of the simulated SWOT measurement in the California Current. For SWOT nadir validation, we will focus on comparing the SSH profiles along the nadir track and the two locations in the KaRIn swath: the inner edge and the midswath.

c. the SWOT nadir validation

The SWOT validation involves comparing the new KaRIn measurements with the truth. In this case, the truth is the ocean signal at nadir observed by the onboard Jason-class nadir altimeter (FU14). The nadir track does not collocate with the KaRIn swaths (Fig. 1). This leads to concerns in validating KaRIn measurements using the nadir altimeter. Even if the nadir altimeter observes the truth, we do not know a priori the extent to which the nadir truth represents the SSH observed over the off-nadir swaths. To address this concern, this study performs assessment along two particular tracks in the SWOT swath: 1) the midswath, 35 km off nadir; and 2) the inner edge of the KaRIn swath, 10 km off nadir (Fig. 1). The inner edge has the shortest distance to nadir. The SSH profiles at the two locations are expected to match better than the rest of the swaths. The midswath corresponds to the lowest KaRIn instrument

noise (Esteban-Fernandez 2017). It is important to validate both the inner edge and the midswath to understand the KaRIn measurements from a wide-swath perspective.

Our objective here is simply to look at the ocean signals and their difference between nadir and off-nadir locations in the wavenumber space to identify the most probable wavelength beyond which the nadir altimeter can be used as the reference for validation. As noted earlier, the nadir altimeter cannot resolve ocean signals below about 70-km wavelength due to instrument noise and measurement errors (Dufau et al. 2016). As a result, we do not expect the onboard nadir altimeter to be useful for the validation below 70 km even if the SSH at nadir may represent the SSH off nadir for wavelengths shorter than 70 km. The SWOT KaRIn instrument noise is much weaker than the nadir altimeter noise (Dufau et al. 2016; Wang et al. 2019) and therefore is not explicitly included in the following analyses.

We denote the nadir measurement as $\eta^{\text{nadir}}(y)$ and the SWOT KaRIn measurement as $\eta_{\text{inner}}^{\text{karin}}(y)$ and $\eta_{\text{mid}}^{\text{karin}}(y)$ for the inner edge and midswath, respectively, where y represents the along-track distance. The error is defined as the SSH difference between nadir and the two off-nadir locations; for example, $\epsilon_{\text{inner}} = \eta^{\text{nadir}} - \eta_{\text{inner}}^{\text{karin}}$ for the comparison between the nadir and the inner edge. The nadir scale is then defined as the wavelength where the error spectrum $\hat{\epsilon}_{\text{inner}}(k)$ intersects the true SSH spectrum, either $\hat{\eta}_{\text{inner}}^{\text{karin}}(k)$ or $\hat{\eta}_{\text{mid}}^{\text{karin}}(k)$, where k represents the along-track wavenumber. An example based on the inner-edge comparison for the California Current region is shown in the left panel of Fig. 2. The error (the dashed line) is significantly lower than the model truth for the long wavelengths (>56 km), but becomes larger than the truth for the smaller wavelengths, which is understandable as the signals with shorter wavelengths usually decorrelate faster. In this particular example, the intersection is at 56 km for the inner edge. Recall that the nadir scale is limited by the nadir altimeter instrument noise at 70 km, which sets the limit of the utility of the nadir altimeter even though its signals are comparable to the SWOT measurement at shorter wavelengths.

To perform a global analysis, the synthetic global SWOT swaths are divided into 1000-km segments with a sliding window of 100 km; that is, two segments have a 900-km overlap. The local nadir scale is calculated for each segment through the spectrum analysis and assigned to the center of the segment. The analysis is done on the 1-yr synthetic SWOT data. The resulting nadir-scale diagnoses along the SWOT orbit are gridded to a uniform $2^\circ \times 3^\circ$ resolution as shown in Fig. 3.

FIG. 2. The wavenumber spectrum of the nadir truth (solid curves) and the inner-edge error (dashed curves) based on three regions: (left) at 35.5°N, 125.4°W near the California CalVal site, (center) in the equatorial Pacific at 5°N, and (right) in the Antarctic Circumpolar Current in the Southern Ocean. The intersections are at 56, 96, and 41 km for the three regions (from left to right), respectively.

3. Results

Figures 3 and 4 show the main results. The diagnosed nadir scale is based on the 1-yr synthetic SWOT data. Its annual mean is shown in Fig. 3. Both the inner-edge (top panel) and midswath (bottom panel) results show large values in the low latitudes and smaller values in the mid- and high latitudes. The regions in the Southern Ocean with sea ice influence are masked out. The latitudinal dependence can largely be explained by the SSH spectrum slope. Figure 2 shows three examples of the SSH spectrum and the error spectrum at low and high latitudes. The wavenumber spectrum has a shallower slope in the low latitudes (center panel), which is consistent with Xu and Fu (2012), mostly due to internal gravity waves/tides (Tchilibou et al. 2018) whose variance at small scales (~ 50 km) have relatively larger variance in low latitudes than in high latitudes (Qiu et al. 2018; Wang et al. 2019). As a result, the error-to-signal ratio due to the spatial separation is larger in low latitudes and consequently the nadir scale is large, ~ 100 km in the equatorial Pacific. The SSH wavenumber spectrum slope is much steeper in the high-latitude Antarctic Circumpolar Current (ACC) region (Fig. 2, right). The errors due to spatial separation are relatively small, leading to smaller nadir scales of ~ 41 km in the example.

In general, the energetic regions such as those near the western boundary currents and ACC are the places more favorable for the SWOT nadir validation.

The nadir scale for the inner edge is shorter than that for the midswath because of the inner edge's proximity to the nadir, but the two nadir scales share the same large-scale latitudinal dependence, that is, larger nadir scales at lower latitudes and smaller nadir scales at mid- and high latitudes. The midswath nadir scale is more than 300 km near the equator because the 35-km separation between nadir and midswath locations introduces significant difference.

A single nadir-scale value can be inferred from the probability distribution function (PDF) of the global nadir scale (Fig. 4). The PDF based on the inner edge (blue) shows a systematic shift to lower values relative to the one based on the midswath (orange). The two PDFs peak at 45 and 120 km for the inner edge and the midswath, respectively. The PDFs have long tails over the long wavelengths, which are associated with the large nadir scale at the low latitudes.

This assessment is different from what is given in Wang et al. (2018). The nadir-scale analysis in the appendix of Wang et al. (2018) was conducted in the California Current, while this study is based on global statistics. It is important to note that the nadir validation

FIG. 3. The annual mean nadir scale based on (top) the inner-edge and (bottom) the midswath locations. The regions with sea ice influence are masked out. The three red symbols in the top panel mark the locations of the three examples shown in Fig. 2.

does not have geographical constraint since the nadir altimeter is *on board* and measurements are continuous. These two peak numbers in this analysis (i.e., 45 and 120 km for the inner edge and midswath) can be used as a guideline for understanding the difference between nadir and KaRIn swath and estimating nadir-validation wavelengths. The 45 km for the inner edge cannot be achieved because the nadir-looking altimeter can only resolve spatial scales larger than ~ 70 km. The midswath value is considered to be representative of the nadir scale of the wide-swath KaRIn measurements.

4. Conclusions and discussion

The SWOT mission requires calibration and validation of the SSH wavenumber spectrum at wavelengths between 15 and 1000 km. The short-wavelength CalVal requires in situ observations. The long-wavelength CalVal will use the onboard Jason-class nadir altimeter.

Using a high-resolution global ocean simulation, this study examines the scales larger than which the nadir and off-nadir observations can be considered comparable. The results suggest that the ocean signals at nadir can represent off-nadir ocean signals at wavelengths longer than 120 km for midswath of the KaRIn grid, indicating that the nadir altimeter is able to fulfill its goal to validate the long-wavelength KaRIn measurement, possibly down to 120 km. Smaller wavelength (45 km) can be found for the inner edge; however, it is not achievable and is limited by the resolution of the nadir altimeter at about 70 km. The nadir validation for both the inner edge and midswath is possible for wavelengths longer than 120 km.

The capability of the onboard nadir altimeter for the validation directly influences the mission's in situ CalVal design in terms of the spatial scales. Wang et al. (2018) showed that the nadir scale is about 150 km in the California Current where the in situ CalVal will

FIG. 4. The probability function of the globally sampled nadir scale based on the inner-edge (blue) and the midswath (orange) locations. The peaks in the two PDFs are at 45 km (blue) and 120 km (orange).

probably occur. Based on a high-resolution global ocean simulation, it is shown here that the 150-km-long glider array described in Wang et al. (2018) can possibly be reduced to 120 km. At longer wavelengths, the nadir altimeter will provide the validation.

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