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Special Section:
Science from the Surface Water and Ocean Topography Satellite Mission

The Surface Water and Ocean Topography Mission: A Breakthrough in Radar Remote Sensing of the Ocean and Land Surface Water

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Key Points:

- The first space observations of submesoscale ocean surface topography for understanding ocean's role in heat uptake from the atmosphere
- The first space observations of the change of water storage of lakes and flow rates of rivers for understanding the freshwater cycle
- The first space observations of the details of the change of coastal water levels to assess the impact of local sea level rise

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Abstract The elevations of water surfaces hold important information on the earth's oceans and land surface waters. Ocean sea surface height is related to the internal change of the ocean's density and mass associated with ocean circulation and its response to climate change. The flow rates of rivers and volume changes of lakes are crucial to freshwater supplies and the hazards of floods and drought resulting from extreme weather and climate events. The Surface Water and Ocean Topography (SWOT) Mission is a new satellite using advanced radar technology to make headway in observing the variability of the elevation of water surfaces globally, providing fundamentally new information previously not available to the study of earth's waters. Here, we provide the first results of SWOT over oceans, rivers, and lakes. We demonstrate the potential of the mission to address science questions in oceanography and hydrology.

Plain Language Summary Earth is a water planet. The vast amount of ocean water has stored most of the heat released to the atmosphere since the Industrial Revolution through burning fossil fuels. Climate change is thus moderated by the ocean. Over land the freshwater in lakes, rivers, and reservoirs, a critical natural resource, is affected by the warming climate and direct human modifications. Processes of oceanic uptake of heat and carbon from the atmosphere and cycling of freshwater on land take place at spatial scales too small to have been adequately quantified from space. A new satellite, the Surface Water and Ocean Topography (SWOT) mission, was launched in December 2022. Using advanced radar technology, SWOT provides unprecedented global observations for understanding the ocean's role in climate change and how freshwater resources respond to human influence. SWOT observations near coasts will also advance understanding of how rising sea levels impact those coasts.

1. Introduction

Earth is a water planet. Human civilization is linked to the exploration of and quest for water. Remote sensing of the vast amounts of ocean and global freshwater is crucial to the study of climate change and its impact on society. Radar remote sensing is particularly important because it penetrates cloud cover, providing observations under all weather conditions. Forty-five years ago, Seasat, the first satellite designed for studying the ocean from space, laid the foundation of radar remote sensing of the ocean with radar altimeter, scatterometer, and synthetic aperture radar (SAR) observations. The first two have become the pillars of a global observing system that has revolutionized oceanography.

Although the precise measurement of sea surface height by radar altimetry has provided a modern record of global sea level change and the large-scale ocean circulation, its spatial resolution is limited by the large radar footprint (~10 km) and measurement noise. This limitation has made it difficult to study small-scale ocean processes, especially near coasts, as well as rivers and lakes, where, despite recent advances in data processing, the geometric properties of nadir altimeter observations (and their one-dimensional spatial extent) have complicated the use of radar altimetry for hydrologic applications (Le Gac, et al., 2021).

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While SAR provides high-resolution images (e.g., 10 m resolution of Sentinel 1 SAR data) of many features of the ocean and land waters, it is difficult to derive the quantitative information needed to study the underlying physical processes. Use of the phase differences of consecutive SAR observations has revealed the slow movement of ice sheets since the early 1990s (Goldstein et al., 1993; Massonnet et al., 1993). The technique is called synthetic aperture radar interferometry (InSAR). In the early 2000s, a demonstration mission of InSAR was conducted onboard the Space Shuttle to map the earth's land topography (Farr et al., 2007). The concept of applying radar interferometry onboard a satellite to oceanography and terrestrial hydrology was developed in the 2000s (Biancamaria et al., 2016; Fu & Rodriguez, 2004; Morrow et al., 2019; Rodriguez et al., 2017). Twenty years later the Surface Water and Ocean Topography (SWOT) mission was launched in December, 2022. Using two SAR antennas separated by a 10 m mast for interferometry in orbit, SWOT provides the first two-dimensional high-resolution measurement of water elevations from space. SWOT is a joint mission of NASA and CNES (the French Space Agency), with contributions from the Canadian Space Agency and the UK Space Agency. The nominal life of the mission is 42 months, with the first 3 months for engineering check out, followed by 3 months for calibration and validation, then a minimum of 36 months for global mapping.

In this paper we present early results from the mission. The fundamental advance of the mission is the capability to observe the elevation of water surface with the high resolution provided by SAR. The elevation precision and the spatial resolution are improved from that of conventional altimetry by an order of magnitude, enabling the study of small-scale ocean eddies and fronts that are essential to the ocean's heat and carbon uptake from the atmosphere. On land, for the first time, the mission is making a global survey of volumetric changes in the world's rivers, lakes, and reservoirs. This new capability opens a new path to advancing the study of the small-scale ocean processes affecting climate change and the critical resources and hazards associated with rivers, lakes and wetlands. Furthermore, the increased resolution will advance the study of near-shore processes to assess the coastal impact of sea level rise and severe weather, including in river deltas and estuaries.

2. Small-Scale Oceanic Processes

For the past 30 years radar altimetry has been used for observing the ocean topography (the shape of sea surface height) over a wide range of scales, from the basin-wide gyres of ocean circulation to large mesoscale eddies (circa 200 km in wavelength) (Ballarotta et al., 2019). The radar measurement noise has limited the along-track resolution to ∼50 km (Vergara et al., 2019). In order to discern the two-dimensional structure of ocean topography, it is necessary to combine measurements from several altimeters, limiting the two-dimensional resolution to 200 km in wavelength from a combination of 3 altimeters. The radar system of SWOT, called the Ka-band radar interferometer (or KaRIn), makes measurements over a swath of 120 km (with a 20 km nadir gap that is sampled with coarse resolution along the centerline by a conventional altimeter), providing the first direct observations of ocean topography and land surface water in two dimensions. The high resolution of the radar system allows averaging of a large number of pixels to reduce noise and still resolve small-scale signals.

2.1. Spectral Analysis

Along-track wavenumber spectra are used in oceanography to study the cascade of energy between large and small-scale ocean dynamics, and also to characterize the statistical noise level of different radar altimetry technologies. The along-track wavenumber spectrum of sea surface height from KaRIn is shown in Figure 1 (in red) in comparison with those from a number of radar altimeters, including the nadir altimeter onboard SWOT. The flattening of the spectra at wavenumbers higher than about 0.02 cyc/km (wavelengths shorter than 50 km) reflects the effect of measurement noise in the nadir radar altimeters. The comparison of the simultaneous measurements by KaRIn and SWOT nadir altimeter demonstrates the consistency of the two at wavelengths longer than 100 km. However, only the KaRIn measurement can reveal the spectrum of smaller-scale ocean processes down to wavelengths of 5 km where the KaRIn spectrum flattens. Many factors affect the data at high wavenumbers. The instrument noise cannot be determined rigorously from the 2-km data used to compute the KaRIn spectrum. Preliminary analysis of the high-resolution KaRIn data suggests that the standard deviation of the instrumental noise in the 2 km data product appears to be somewhat smaller than 0.4 cm. More rigorous analysis of the KaRIn signal-to noise performance, which involves many complicated factors, is still being studied.

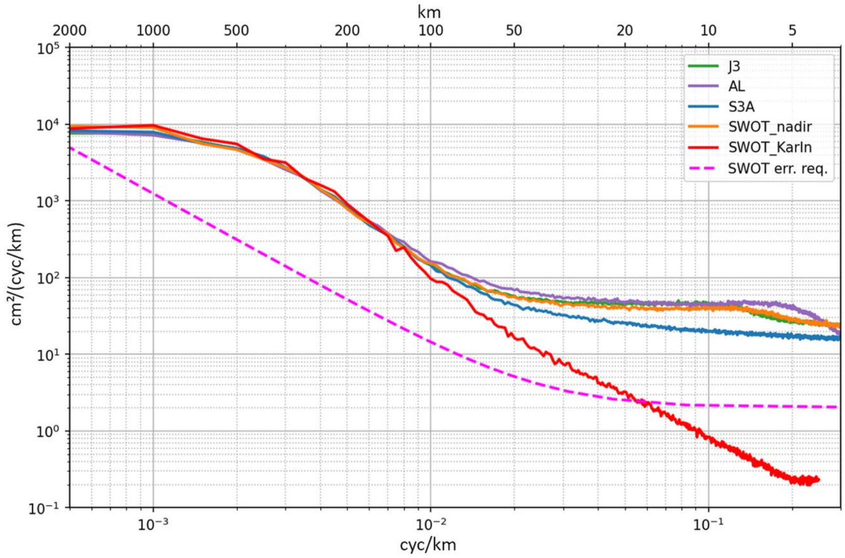

Figure 1. Along-track wavenumber spectrum of sea surface height from KaRIn (in red color) in comparison with those from a number of radar altimeters (J3-Jason-3, AL-Altika, S3A- Sentinel-3A), including the nadir altimeter onboard Surface Water and Ocean Topography (in orange color). Mean global spectra are calculated from the data from 1–14 May 2023. For KaRIn, the data are analyzed from the center of each swath. The pink dashed line represents the mission requirement for the KaRIn measurement errors.

The mission's design requirement for the spectrum of KaRIn measurement errors (JPL-D61923, 2018) is also shown in the pink dashed line. The design requirement was formulated in such a way as to achieve an expected resolution of ocean signals to 15 km in wavelength, where the requirement spectrum flattens. As shown in Figure 1, the apparent noise power of KaRIn is lower than the requirement by an order of magnitude. The resolved wavelength of 5 km is shorter than the 50 km resolution of conventional altimeters also by an order of magnitude.

The KaRIn measurement has exceeded the requirement by an order of magnitude, showing the continuing cascading of ocean circulation processes from large to small scales down to ~5 km in wavelength, which was previously not observable from space. The small ocean eddies and fronts observed by SWOT may be responsible for a substantial fraction of the vertical transport of heat, nutrients and other biochemical constituents of the ocean (Lapeyre & Klein, 2006). The observations of SWOT will go a long way toward advancing the understanding of small-scale ocean circulation that is crucial for assessing the ocean's capacity to continue absorbing heat and carbon dioxide from the warming atmosphere.

2.2. Small-Scale Ocean Eddies and Fronts

Displayed in Figure 2 is an example of the KaRIn observations over a stretch of the ocean in the Gulf Stream region off Cape Hatteras compared with the observations made by a combination of conventional nadir radar altimeters. Even with seven state-of-the-art nadir altimeters in orbit, the coarse resolution is revealed by the blocky cells on the image, whereas the image of KaRIn shows the details of the sea surface height anomalies of the fluctuating Gulf Stream and associated eddies and fronts. These small-scale features have been observed from space only by visible and infrared sensors of sea surface temperature and color (e.g., Castro et al., 2017), albeit limited to cloud-free days. Furthermore, sea surface height, being proportional to the ocean pressure field, is more directly relevant for studying ocean interior dynamics than the surface tracer fields like ocean color and sea surface temperature.

The temporal scales of ocean processes generally decrease with their spatial scales. SWOT was launched into a special orbit that overflew any given location within the measurement swath every single day and collected data in this orbit between 29 March and 11 July 2023. The purpose of this Calibration and Validation (CalVal) orbit is three-fold: First, the rapid-repeat orbit allows many more overflights of CalVal ground-truth stations in a relatively short period of time. Second, the measurement errors are affected by rapidly changing oceanic and atmospheric conditions. The daily observations allow the assessment of such measurement errors. Third, there are

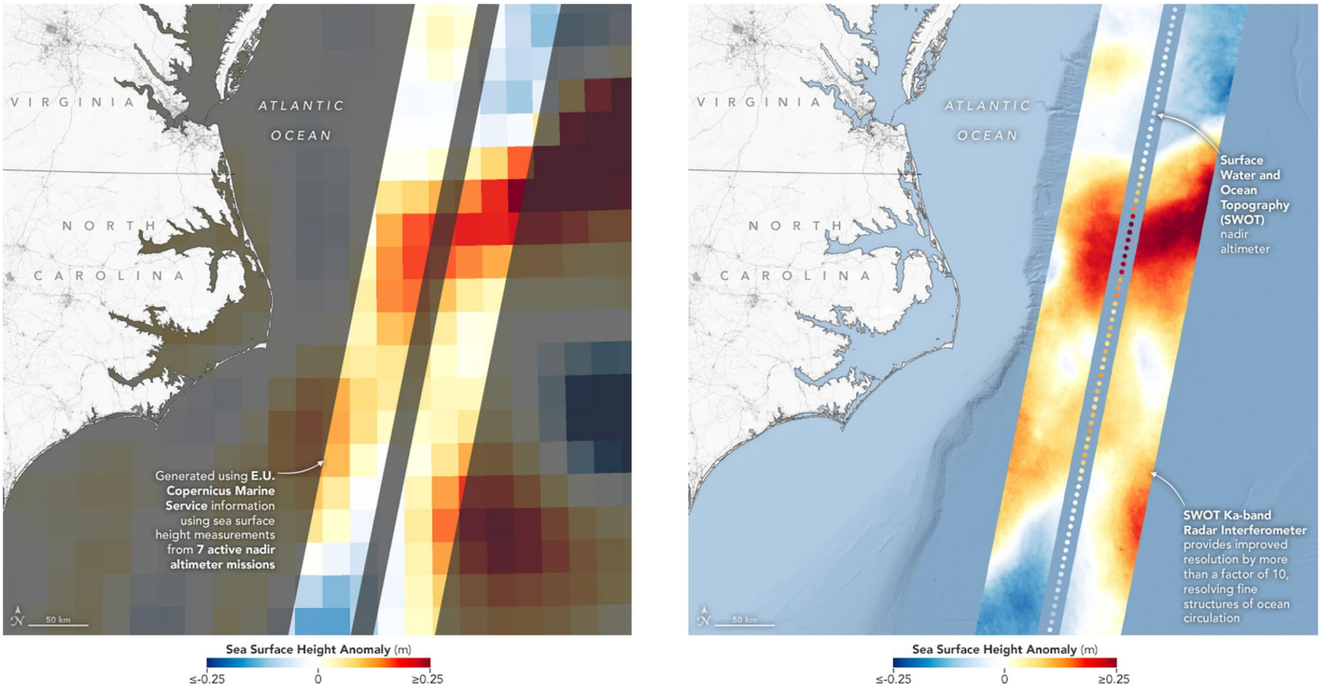

Figure 2. Comparison of the observations made by KaRIn over a stretch of the ocean in the Gulf Stream region off Cape Hatteras (right panel) with the observations made by a combination of radar altimeters (left panel).

also rapidly changing ocean signals such as tides and waves that are observed by KaRIn. A challenge is to separate signals and errors in a KaRIn snapshot image.

On 21 July 2023, SWOT transitioned to a global mapping phase in which the satellite covers nearly the entire earth from 78°S to 78°N in approximately 21 days. Data collection in this orbit started on 26 July. Note that the earlier CalVal orbit samples only a very limited part of the earth due to its widely separated satellite ground tracks in the 1-day exact repeat orbit. In the 21-day orbit, the swath coverage gradually weaves a pattern to cover the entire surface of the earth overflown by SWOT. What is learned from the 1-day repeat CalVal orbit is crucial to the interpretation and analysis of the observations made in the mapping phase.

2.3. Internal Solitary Waves

The high resolution of KaRIn has captured a wide range of ocean phenomena. Although the major oceanographic objective of SWOT is to advance the understanding of small-scale ocean eddies and fronts, it turns out that a variety of other processes in the ocean are also observed by KaRIn, making the analysis of the observation both interesting and challenging. An example of such processes is shown in Figure 3. This swath covers a stretch of the ocean in the Molucca Sea, where the rough bottom topography interacts with ocean tides creating the patterns of internal solitary wave trains, shown as packets of wave groups with a leading edge followed by a series of wave fronts with decreasing amplitudes and separations. This is the classical pattern of internal solitary waves made by SAR from Seasat (Fu & Holt, 1984).

Since Seasat there have been numerous studies of internal solitary waves from radar as well as sunglint images over a wide range of locations of the world's oceans (Jackson, 2007; Magalhães et al., 2021). Through generation by interaction of tidal currents with bottom topography, these waves is tied to the local tidal cycle. Their wavelengths are only a few km, far too short to be observed by a radar altimeter. Although these energetic waves have been surveyed by spaceborne SAR over decades, SAR images of surface roughness do not have information on the magnitude of surface perturbations that are related to the energetics of the waves. Previous studies made inferences on the energy carried by these waves, suggesting possibly 10% of tidal dissipation could be accounted for by generating internal solitary waves over rough bottom topography (Magalhães et al., 2021). For the first time, SWOT will provide joint SAR images and elevation maps over these waves. Their survey by SWOT in the

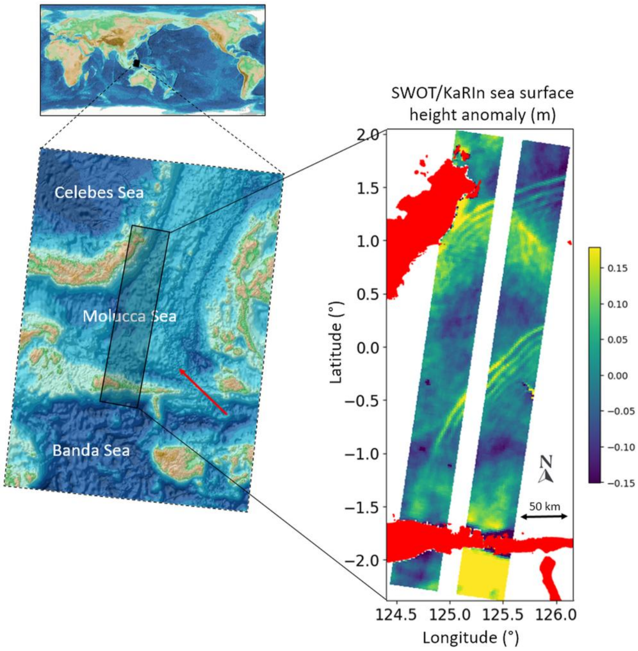

Figure 3. Surface Water and Ocean Topography (SWOT) observations of the surface elevations (in m) of Internal solitary waves in the Molucca Sea in the western tropical Pacific. Red areas are land. The geographic location of the SWOT observations is illustrated by the world and regional maps.

mapping phase will lead to a global estimate of their energy and their role in the dissipation of ocean tides. The distinct two-dimensional pattern of these waves makes it easier to detect and separate them from the large-scale geostrophically balanced ocean processes.

3. Observations of Rivers and Lakes

In the last decade, satellite imagery has increasingly been used to study global patterns of water storage and fluxes in rivers (Koblinsky et al., 1993), lakes (Crétaux & Birkett, 2006) and floodplains (Birkett, 1998). However, these studies have been limited by the available data. Most lakes worldwide are missed by existing radar-based altimeters, which measure water height only at nadir (Alsdorf & Lettenmaier, 2003), and the extremely limited temporal resolution of laser-based systems such as ICESat-2 reduce their utility (Cooley et al., 2021). In addition, the one-dimensional nature of these measurements means that attempts to estimate river discharge and lake water storage from space require incorporation of data from ground-based sources or other satellites (Crétaux et al., 2016; Emery et al., 2018; Tarpanelli et al., 2022), which are rarely available at the same time. Moreover, monitoring inundation depths over floodplains, particularly in ungauged basins, is a very challenging issue, barely achievable from current satellite data. The combination of satellite altimetry with some global data sets based on microwave sensors is doable, but the resulting uncertainties are not easily measurable and may be large (Papa & Frappart, 2021).

SWOT addresses these limitations, and preliminary results suggest that it will allow robust, simultaneous observation of changes in water surface elevation and inundation extent in the world's lakes, rivers, floodplains and reservoirs. First results from SWOT over the Yukon River Delta in Alaska show its capabilities in both rivers and lakes (Figure 4a). This image was created using the SWOT Level 2 Lake Single Pass (LakeSP) and Level 2 River Single Pass (RiverSP) data products collected on 18 June 2023. In just this figure, we observe elevations for several thousand lakes as small as one ha. Elevations are spatially coherent, suggesting relatively low measurement noise. Meanwhile, edges of lakes closely match observations from high resolution optical satellite imagery (Figure 4b). Indeed, examination of the SWOT pixel cloud data product, the finest scale of georeferenced SWOT data, shows that many water bodies smaller than one ha are clearly visible to SWOT (Figure 4c), in addition to the larger lakes shown in Figure 4a. The SWOT pixel cloud data product represents SWOT elevation and inundation extent measurements in a formatl similar to a lidar point cloud, with each pixel covering a defined area. The SWOT Prior Lake Database (PLD) includes only lakes larger than 1 ha, but it may require revision based on SWOT's better than expected performance in this area. No data source prior to SWOT could provide such detailed simultaneous lake water surface elevation and extent measurements. Meanwhile, river slopes are clearly visible in Figure 4a, even along relatively shallowly sloping rivers such as the mainstem of the Yukon, which descends from east to west at a grade of less than 10 cm/km in many of the reaches shown here.

We also show preliminary SWOT observations over the Tsiribhina River (Figure 5), which is located in the central part of Madagascar and flows from the central hills in the direction to the Mozambique Channel. It has a drainage area of 49,800 km^2, occupied mostly by grassland, and it is of high importance to the country for rice production (a quarter of the total production of the country). The climate is semi-humid tropical, and it has a wet season from November to March and a dry season covering the rest of the year (Andriambeloson et al., 2020). During the validation phase of SWOT (starting in April 2023), in the dry season, the river level decreased very rapidly. During 9 days of fieldwork in the beginning of April, the river height changed by more than a meter (measured using a kinematic GNSS receiver), which compares favorably with SWOT. The first daily SWOT images during this period, collected between 4 and 8 April 2023, observe a water leve increase of 1.06 m (an increase of 0.95 m was measured in situ), and from the 8 to 12 April SWOT measured a drop of 93 cm, while the in situ sensors measured a drop of 1.12 m. The slope of the river, which based on field data in the western part is about ∼20–30 cm/km, was also effectively measured by the KaRIn interferometer on SWOT (Figure 5).

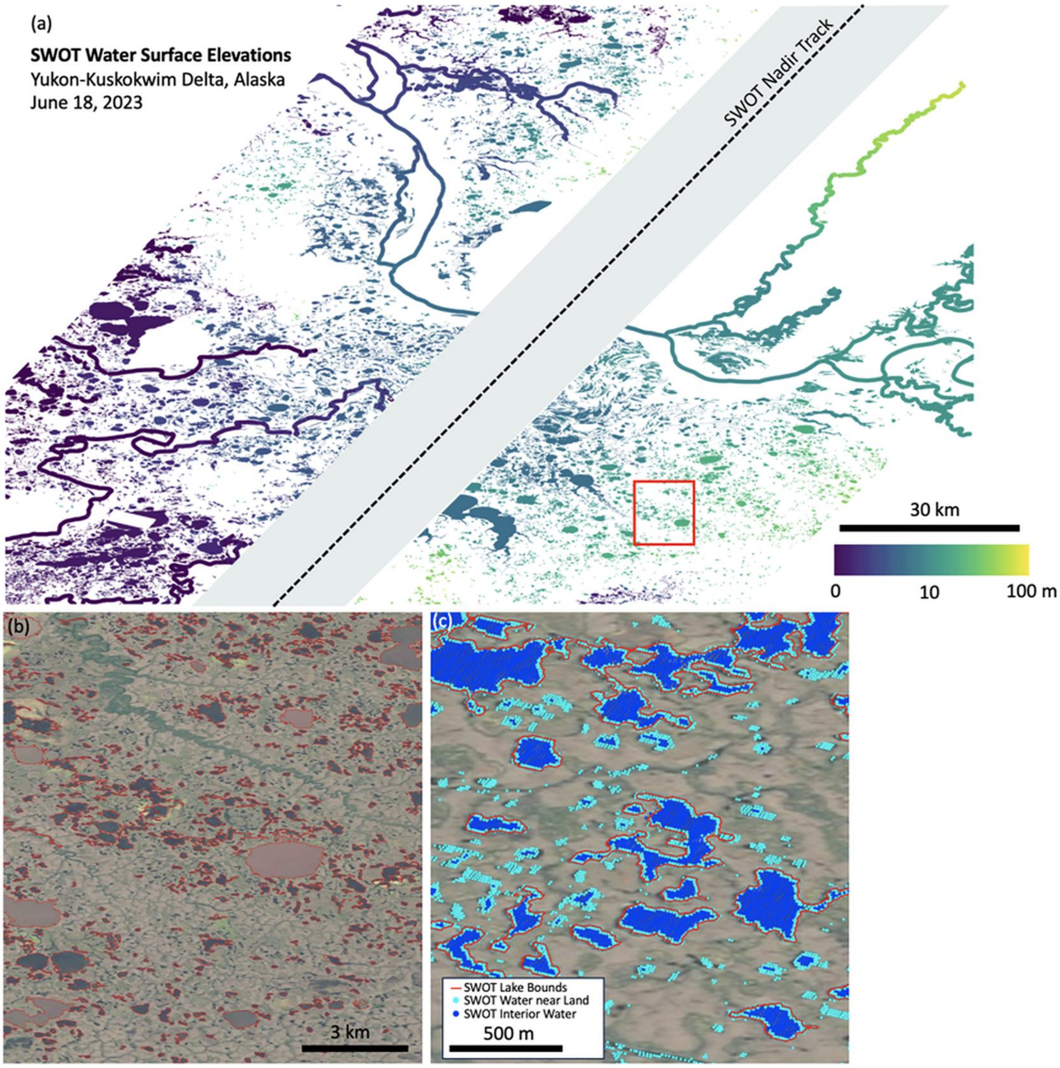

Figure 4. (a) Surface Water and Ocean Topography (SWOT) water surface elevation data from the SWOT RiverSP and LakeSP data products for 18 June 2023 over a portion of the Yukon River Delta in Alaska. (b) Zoom-in of SWOT lake boundaries overlaid on high resolution optical imagery showing the close correspondence between SWOT-derived boundaries and this imagery. (c) Further zoom in showing SWOT lake boundaries in red and SWOT water pixels from which they are derived. Note that many lakes smaller than 1 ha are visible in SWOT pixel cloud data, illustrating SWOT's capabilities to observe water bodies even smaller than original mission goals.

In some cases specular reflection, in which a smooth, mirror-like surface results in the satellite's emitted signal being reflected away from the satellite rather than back to the sensor, leads to low measurement signal. We term this phenomenon dark water. However, in this case sufficient pixels were obtained to measure the river height at nodes and the river slope on each of the reaches from the SWOT River Database (SWORD; Altenau et al., 2021). A large number of small to medium size lakes (a few square kilometers in area), that are identified in the PLD, were also observed by SWOT. SWOT will be extremely useful in such ungauged basins, which often fall in economically vulnerable areas dependent on local agriculture.

Based on preliminary evidence, SWOT has the capability to meet or exceed its science requirements for monitoring lakes and rivers (i.e., lakes larger than 250 × 250 m, and rivers wider than 100 m). Further analysis will be required for robust, quantitative validation. SWOT measurements will allow space-based inference of lake water storage (Biancamaria et al., 2016) and river discharge (Durand et al., 2023) to complement geographically limited ground-based measurements. Our preliminary results suggest that SWOT can measure these key variables crucial

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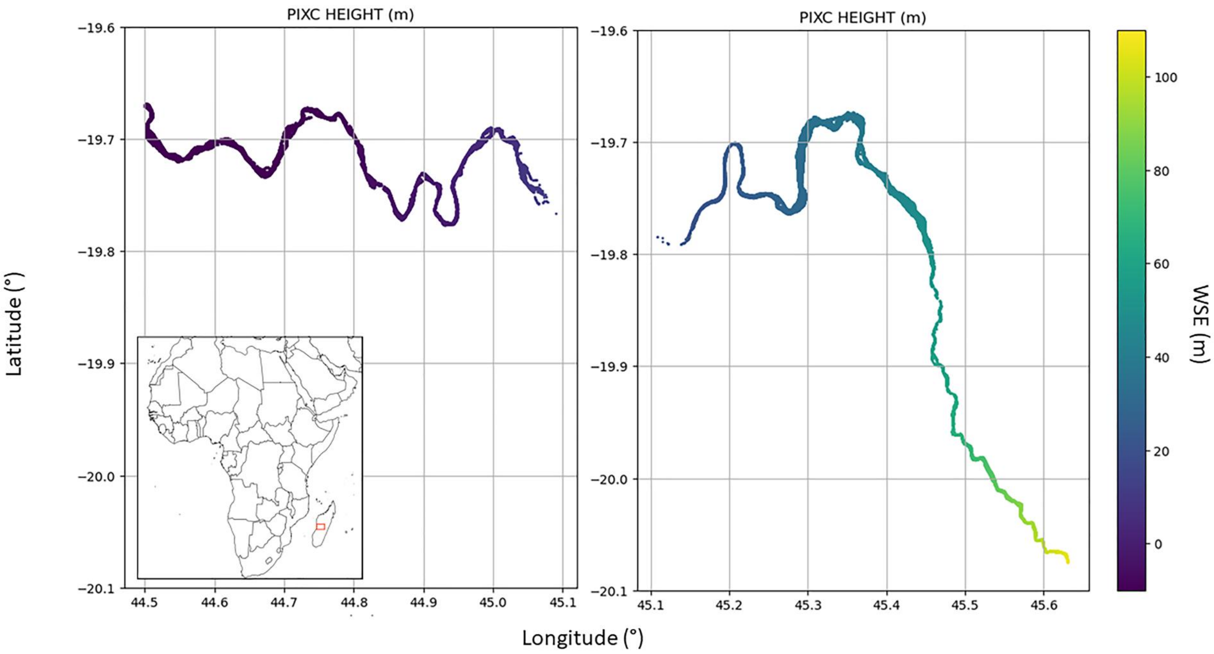

Figure 5. Surface Water and Ocean Topography (SWOT) pixel cloud observations over the Tsiribihina river on 9 April 2023. Water Surface Elevation from upstream to downstream measured by SWOT along the river is as high as 100 m and drops to approximately sea level.

to the study of the global water cycle for nearly 6 million lakes and approximately 160,000 ∼10 km river reaches (Altenau et al., 2021).

4. Conclusions

Preliminary results from the SWOT Mission show the potential to markedly improve understanding of earth's waters, including the ocean's role in our changing climate and the drivers of dynamics in rivers, lakes, and reservoirs. The high-resolution information regarding elevation change in coastal oceans, estuaries and river deltas will allow assessment of the localized impact of sea level rise with a spatial granularity previously unavailable. Over continental waters, SWOT will fill substantial gaps in monitoring of lakes, rivers, and wetlands, allowing global estimation of variables such as variations in reservoir storage and river discharge that are important to both the global water balance and water resource management. The rapid changes of the ocean and land surface waters revealed by the 1-day repeat data pose a challenge to the analysis of the 21-day repeat data from the global mapping phase of the mission. The information provided by the 1-day repeat data on the underlying mechanisms controlling these rapid changes is key to meeting this challenge and to reaping the rewards from a wealth of new global information about the earth's waters.

Data Availability Statement

All datasets used in this manuscript are preserved and distributed by the Agencies' data repositories in compliance with FAIR requirements (e.g., Core Trust Seal certified or ongoing certification from the Research Data Alliance).

- The SWOT products used in the manuscript are distributed by mirror centers from NASA and CNES. The SWOT products can be downloaded from either repository. Each SWOT product has a specific product description document (PDD) and digital object identifier (DOI).
  NASA (2023) is the PODAAC repository for both ocean and hydrology products
  CNES (2023b) is the AVISO repository for ocean products
  CNES (2023a) is the HYDROWEB repository for hydrology products.
- Among the variety of SWOT products available on the repositories, this paper specifically uses four products:

The SWOT Level 2 KaRIn Low Rate Sea Surface Height Data Product, Version 1.1 is available in SWOT Project (2023b).

The SWOT Level 2 KaRIn High Rate River Single Pass Data Product, Version 1.1 (PODAAC, collection ID:SWOT_L2_HR_RiverSP_1.1) is available in SWOT Project (2023a).

The SWOT Level-2 KaRIn High Rate Lake Single Pass Data Product, Version 1.1 (PODAAC, collection ID:SWOT_L2_HR_LakeSP_1.1) is available in SWOT Project (2023f).

The SWOT Level-2 Nadir Altimeter Data Product (AVISO, collection: L2_NALT_IGDR) is available in SWOT Project (2023c).

- This paper also uses Level-3 products from other altimetry missions (namely Sentinel-3, Jason-3, SARAL) in Figure 1, as well as Level-4 gridded products other nadir altimetry satellites in Figure 2. These datasets are available in Copernicus Marine Service repository (2023).

The Level-3 along-track product is available in SWOT Project (2023d).

- The Level-4 gridded product is in SWOT Project (2023e).
- The SWOT Level-1 and Level-2 products were generated by the SWOT satellite ground segments from NASA (offline reprocessing) and CNES (near-real time processing), using algorithms and processors documented on the PODAAC repository. The Algorithm Theoretical Basis Documents (ATBD) describing said algorithms and processors is open and available in PODAAC (2023). The NASA ground segment is operated on the Amazon Web Services (AWS). The CNES ground segment is operated on a proprietary datacenter using the same software. The figures from this manuscript were produced with a combination of open source software libraries and packages from the PANGEO project (e.g., jupyter, dask, xarray, matplotlib).
- The optical imagery in Figures 4b and 4c is standardized background imagery from Google and is an amalgam of Landsat, Sentinel 2, and Maxar data.

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