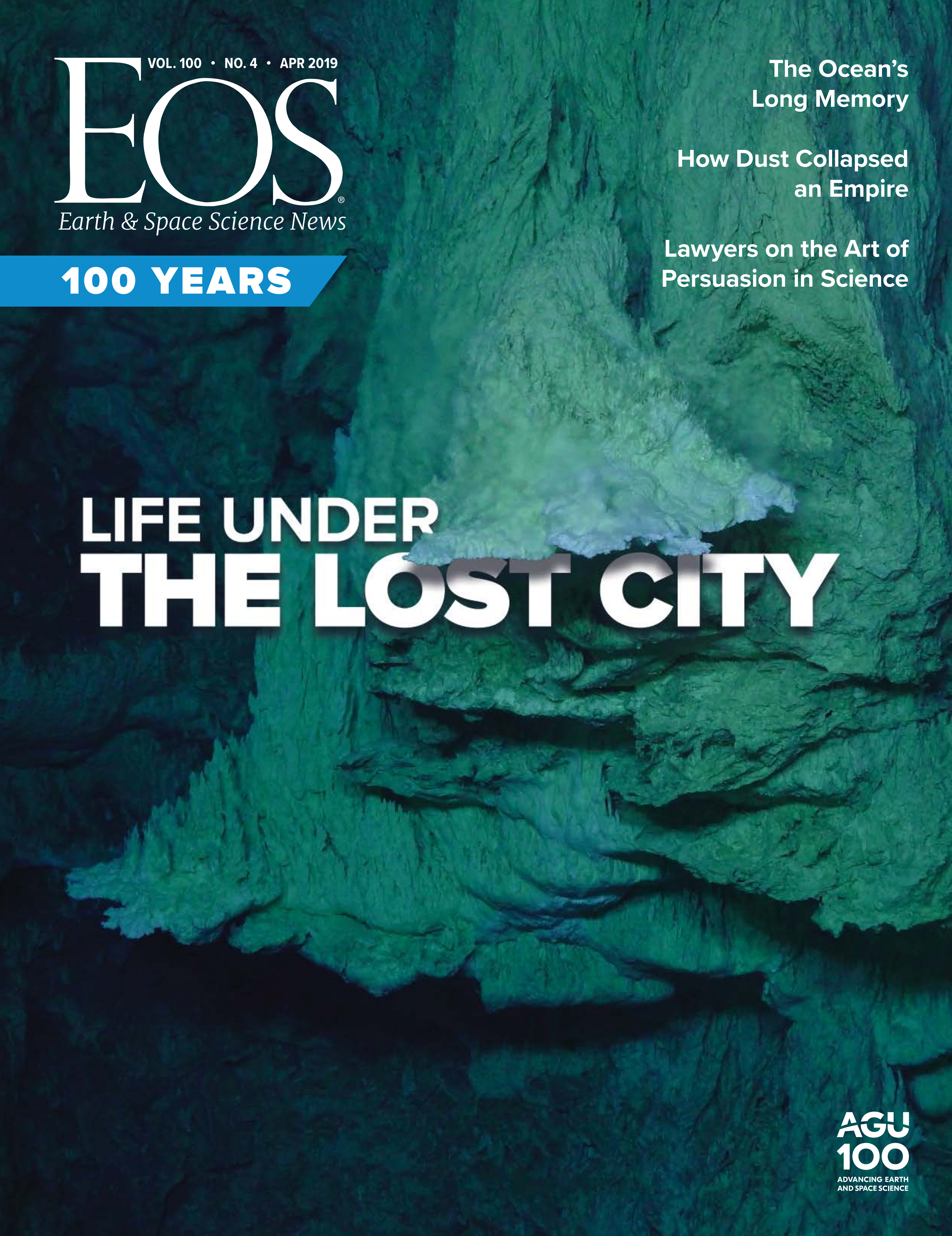

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ADVANCING EARTH AND SPACE SCIENCE

SCIENTISTS INVITED TO COLLABORATE IN OCEAN OBSERVING MISSION

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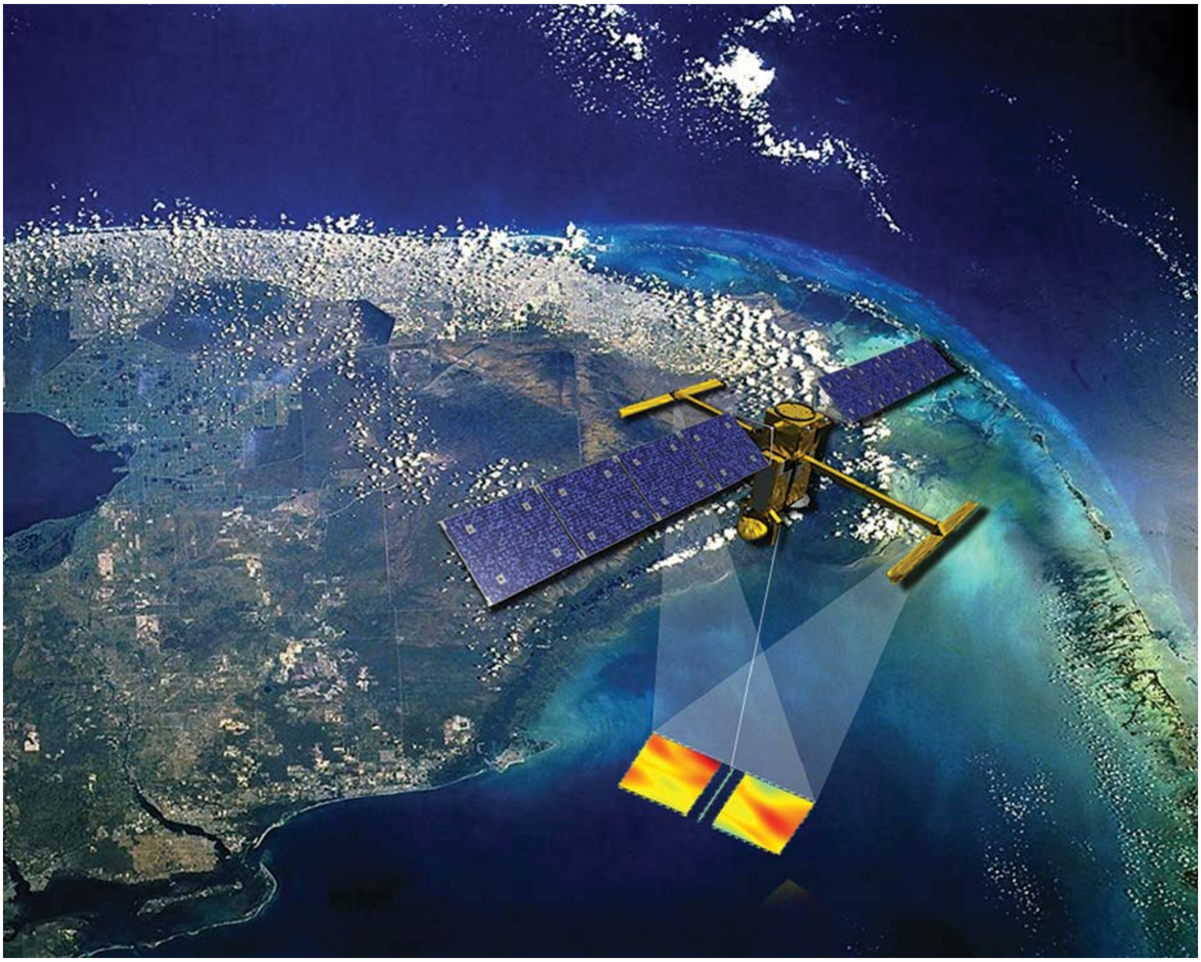
Francesco D’Ovidio, and J. Thomas Farrar

Sea level is sea level, no matter where you go, right? Not necessarily. The Moon’s gravitational pull, ocean currents, melting glaciers, and a host of other factors ripple and distort the surfaces of the world’s oceans. Water levels in lakes, rivers, reservoirs, and other inland bodies are constantly changing as well, in response to floods, droughts, and human water use.

The Surface Water and Ocean Topography (SWOT) satellite mission, due to be launched in 2021, will map the elevation of water surfaces on Earth at a resolution that has not been possible before. This mission aims to improve estimates of sea surface elevations and the volumes of water stored in lakes, reservoirs, wetlands, and rivers around the world.

SWOT is scheduled to map the entire globe between 78° north and south latitude over the course of 3 years. Before it settles into its main orbit, covering Earth’s surface every 21 days, the first 90 days of the mission will be flown in a “fast-sampling” phase, revisiting each area once daily.

We are inviting members of the international ocean science community to participate in this unique fast-sampling phase. We encourage you to create programs to deploy in situ assets in the



Artist's rendering of the future SWOT satellite making sea surface height observations, even through clouds. Off-nadir radar interferometers gather data over two 60-kilometer-wide swaths at once, with a conventional nadir altimeter in between. Credit: CNES

regions covered by the SWOT fast-sampling orbit to provide a global series of experiments with fine-scale ocean campaigns, as well as ground-based data for comparison with SWOT's daily 2-D sea surface height data.

A High-Resolution Look at the World's Oceans

Today's multimission satellite altimeter maps show sea level undulations, from large eddies up to basin-scale or global variations. We cannot resolve the smaller eddies with diameters less than 75 kilometers because their signal gets lost in the noise. These unresolved 75-kilometer-wide eddies have a spectral wavelength of 150 kilometers; this defines the minimum spatial wavelength that we can resolve today.

SWOT will rely on a satellite altimeter that will use radar interferometry to make high-resolution (~2-kilometer) measurements over two 50-kilometer-wide swaths of water at once, with a conventional nadir altimeter in the gap in between.

This new SWOT measurement will extend the 2-D resolution of ocean surface topography down to between 15 and 45 kilometers in wavelength, detecting small eddies with diameters of 7–20 kilometers , depending on ocean surface conditions. This advance will offer researchers new opportunities to study the oceanic dynamic processes at these scales over the global oceans [*Fu and Ubelmann,* 2014].

SWOT aims to bring new insight into ocean processes at scales of 15–150 kilometers in wavelength that have typical temporal scales of hours to weeks [*Fu and Ubelmann,* 2014]. A number of dedicated local in situ campaigns have provided insight into these rapidly evolving submesoscale dynamics (e.g., the Lateral Mixing Experiment (LATMIX) and the Ocean Surface Mixing, Ocean Sub-mesoscale Interaction Study (OSMOSIS)) and the internal wave dynamics (e.g., internal wave experiment (IWEX), Ocean Storms). Globally, our current knowledge on the fine scales is based largely on untested simulations of high-resolution circulation models. SWOT will address this observational gap and provide an unprecedented opportunity to study the surface signature of these motions and their interactions.

These fine-scale processes are important in the generation and dissipation phases of ocean mesoscale eddies, and they provide both sinks and sources for the ocean's kinetic energy at larger scales. They also act as one of the main gateways that connect the interior of the ocean to the upper layer: The active vertical exchanges linked to these

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scales may have important impacts on the local and global budgets of heat, carbon, and nutrients. Ocean stirring can be a main controller of oceanic fronts and plankton diversity and thus of the ocean ecosystem services. SWOT is therefore positioned to play a key role in studying the ocean climate system and in biogeochemical cycles [*Mahadevan,* 2016].

Internal Tides and Gravity Waves

A major challenge and opportunity offered by SWOT's fine-scale sea surface height (SSH) observations is to study the interaction of these balanced ocean motions (driven by Earth's rotation, wind, and buoyancy effects) with the internal tides and internal gravity waves that stir and circulate water beneath the ocean's surface. Whereas a large part of the internal tide is predictable, the internal wave continuum is not.

Modeling studies suggest that the spatial scales at which balanced motions are clearly separated from internal waves in SSH vary geographically and seasonally [*Qiu et al.,* 2018]. Balanced motions tend to dominate in the middle to high latitudes, and internal waves are prominent in the weakly energetic eastern basins and tropical regions. Adequate observation of these processes made simultaneously with SWOT and in situ systems should allow progress on testing methodologies to separate these two entangled motions and to understand their interactions.

A Quick Look at Short-Lived Events

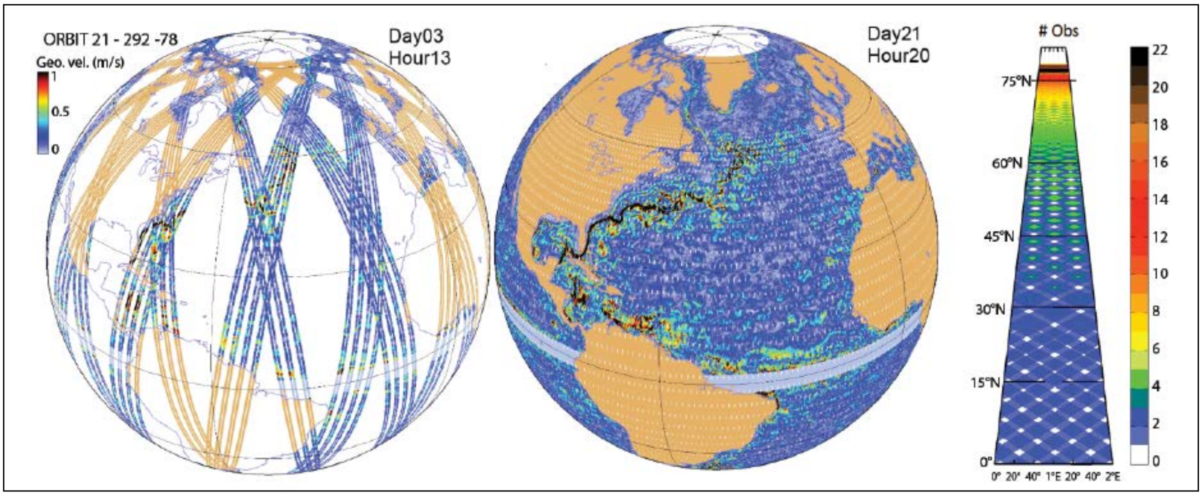
Given the width of the measurement swath, it will take SWOT 21 days to map Earth's entire surface at latitudes lower than 78°. (In the Northern Hemisphere, the 78th parallel circles just north of the coasts of North America and Europe; in the Southern Hemisphere, it passes through Antarctica's coastal regions and the Southern Ocean.)

In its 3-year science orbit, SWOT will loosely cover the global oceans (Figure 1, left) after 10.5 days, then shift westward and fill in the gaps to achieve full coverage after 21 days (Figure 1, middle).

Because of the swath coverage, the number of repeat observations at a given location during the 21-day repeat orbit varies with latitude, from two repeats at the equator to two to four at the midlatitudes to more than six at the high latitudes (Figure 1, right). This rather coarse temporal sampling presents a challenge for the study of the small-scale, rapid ocean processes that have timescales comparable to or shorter than the sampling intervals.

To catch a glimpse of these short-lived processes, the first 90 days of the SWOT science mission will be flown in a fast-sampling phase that revisits specific areas once per day. This phase will begin after a 90-day commissioning phase for engineering checkout and adjustment. Details of the various orbits are available online (bit.ly/SWOT-details). The fast-sampling phase (January to March

Fig. 1. SWOT's nominal orbit coverage up to 78°N and 78°S after 3 days (left) and the full 21 days of a complete cycle (middle). Color shows the modeled surface currents for each track. Geo. vel. indicates surface geostrophic velocity (with the speed of currents in meters per second). (right) The number of observations at a given latitude (shown here for northern latitudes, but the same applies to the south) during the 21-day repeat period. Credits: (left and middle) C. Ubelmann, CLS; (right) JPL/NASA



The payoff would be tremendous in advancing our understanding of the key fine-scale dynamics of the ocean.

2022) is intended for process studies with a reduced coverage, providing observations in the Northern Hemisphere winter and Southern Hemisphere summer (Figure 2). SWOT measurements are not impeded by clouds, so the synoptic maps of sea surface height provided by SWOT will track fine-scale circulation features at daily intervals (twice daily at crossovers) during this fast-sampling phase.

Comparing Snapshots from Earth and Space

The speed of SWOT's measurements poses a challenge to researchers attempting to compare the mission's results with in situ measurements from the surface: SWOT will cover a distance of 150 kilometers in about 20 seconds, providing a nearly instantaneous snapshot of SSH over a 120- × 150-kilometer area. In order to disentangle the substantial contributions of high-frequency motions (such as internal waves) to SSH, we need to observe the 2-D in situ dynamic height on hourly timescales.

Wang et al. [2018] presented a basic design of an in situ observing system involving an array of 20 station-keeping underwater gliders to determine hourly dynamic height over scales of 15–150 kilometers. Alternatives are to use moorings for continuous sampling, combined with fast underway CTDs (instruments that measure electrical conductivity, temperature, and depth), gliders, or profiling floats. To characterize the ocean pressure and velocity field in four dimensions (three spatial dimensions and time), we would need more in situ assets. SWOT's fast-sampling phase will also open opportunities for designing in situ adaptive sampling strategies.

Although SWOT's 2-D radar interferometric technique will reduce the measurement error by more than an order of magnitude compared to today's 1-D along-track altimetry missions, SWOT's actual spatial resolution will vary spatially and temporally, depending on the relative strength of ocean signals and the magnitude of measurement errors. Studies have predicted that SWOT's resolution may approach 35–45 kilometers in low-energy regions or in high surface wave regions.

Coupling Data Sources Yields Big Payoffs

Since the SWOT measurement performance and the oceanic fine-scale signals vary geographically and seasonally, our understanding of the oceanic variability at 15- to 150-kilometer scales would greatly benefit from in situ observations made at different locations during the 90-day fast-sampling phase. Such an ambitious undertaking can be accomplished only through coordinated international campaigns and contributions. The payoff would be tremendous in advancing our understanding of the key fine-scale dynamics of the ocean governing the energy budget and the biophysical processes of the ocean circulation, as well as its role in the climate system.

Diverse in situ deployments covering multiple crossover regions during the 1-day fast-sampling phase would help unravel the complicated dynamic processes contributing to these SWOT SSH snapshots to achieve a truly global fine-scale ocean dynamics experiment.

We encourage the international ocean science community to join us in this unique opportunity by deploying in situ assets in different regions covered by the SWOT fast-sampling orbit. Such in situ efforts would require external funding, but the SWOT mission would enthusiastically welcome these collaborative validation efforts. These projects could be proposed in coordination with the mission's next science team (NASA's Research Opportunities in Earth and Space Science and Centre National d'Etudes Spatiales' Terre, Océan, Surfaces Continentales, Atmosphère issued a request for proposals in February 2019, with selection in late 2019.) The next science team starts in 2020, about 1 year prior to the mission's launch (approximately October 2021).

The preliminary science data from the SWOT mission will be made available to the mission's science team in a timely manner during the fast-sampling phase to facilitate comparisons of the in situ observations with SWOT observations. The in situ results will contribute to the initial calibration and validation of the mission observations, as well as to SWOT's Adopt a Crossover global experiment on fine-scale ocean processes. We encourage interested ocean scientists to contact any of the authors listed below for further information.

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