Eddies in Time Foretell the Future

By John Benson

January 2023

1. Introduction

In case you haven't noticed, approximately 71% of Earth's surface is covered by water. To say that oceans, rivers and other large bodies of water have a major effect on weather and climate is an understatement. However, until recently we have been flying-blind when it comes to one major characteristic of these bodies: what's happening in the third dimension (the depths). If everything goes right, in about six months this gap will be illuminated.

Major electric utility organizations' (like independent system operators (ISOs) and Regional Transmission Operators (RTOs)) short-range planning starts with models that simulate operations for several days. The most important non-utility inputs to these models are weather forecasts. The major advance described in this post will result in much more accurate short-term and longer term weather forecasts. The latter will enable these utilities to extend their planning horizon.

Also, of course, climate change is, or should be, important to everyone. Different models are used to predict future effects of climate change. These too will benefit greatly from the new tool described in this post, and enable more accurate and longer-range forecasts.

2. SWOT

A satellite built for NASA and the French space agency Centre National d'Études Spatiales (CNES) to observe nearly all the water on our planet's surface lifted off on its way to low-Earth orbit at 3:46 a.m. PST on Friday, Dec 16. The Surface Water and Ocean Topography (SWOT) spacecraft also has contributions from the Canadian Space Agency (CSA) and the UK Space Agency.[1]

The SWOT spacecraft launched atop a SpaceX rocket from Space Launch Complex 4E at Vandenberg Space Force Base in California with a prime mission of three years. The satellite will measure the height of water in freshwater bodies and the ocean on more than 90% of Earth's surface. This information will provide insights into how the ocean influences climate change; how a warming world affects lakes, rivers, and reservoirs; and how communities can better prepare for disasters, such as floods.

After SWOT separated from the second stage of a SpaceX Falcon 9 rocket, ground controllers successfully acquired the satellite's signal. Initial telemetry reports showed the spacecraft in good health. SWOT will now undergo a series of checks and calibrations before it starts collecting science data in about six months.

[1] Jet Propulsion Laboratory, "NASA Launches International Mission to Survey Earth's Water," Dec 16, 2022, https://www.jpl.nasa.gov/news/nasa-launches-international-mission-to-survey-earths-water

3. Hidden Ocean Swirls

Eddies have been overlooked for too long. These turbulent swirls of water, ranging in size from a few kilometers to hundreds of kilometers across, peel off large ocean currents and mix heat and carbon dioxide into deeper ocean layers, like cream stirred into coffee. They are the most energetic feature of the ocean, critical to getting climate models right—but also largely invisible to satellites, except when they happen to sweep up a massive bloom of green phytoplankton.[2]

No longer. Eddies and, on land, the ebb and flow of rivers and lakes will snap into focus after the launch of the Surface Water and Ocean Topography (SWOT) satellite, a joint venture between NASA and CNES, the French space agency…

For oceanographers it will be like slipping on a pair of eyeglasses, says -Rosemary Morrow, a physical oceanographer at the Laboratory of Space, Geophysical, and Oceanographic Studies in Toulouse, France. The satellite will capture eddies as small as 7 kilometers across and cover nearly the entire globe every 21 days. On land, SWOT will be able to map the changing height of more than 6 million lakes, from the Great Lakes down to ponds, while also capturing flows in rivers wider than 100 meters. It will replace spotty, infrequent measurements from the ground and make the field of hydrology far more empirical, and global, than it ever has been. "It's going to help us constrain how the water cycle works in the Arctic, Africa—places where we don't have on the ground data," says Tamlin Pavelsky, a hydrologist at the University of North Carolina, Chapel Hill, and co-lead of SWOT's freshwater science team.

For nearly 4 decades, NASA and CNES have launched a series of radar altimeter satellites, which use reflected pulses of radar to measure water height. Those instruments have monitored the accelerating rise of global sea levels, a basic indicator of climate change. By measuring the ocean's bulges and dimples, they also track the large-scale currents that sweep water around the planet. But the satellites' coarse spatial resolution meant rivers and small eddies were out of reach.

SWOT gains a sharper view with the help of two 5-meter booms, each bearing an antenna to catch reflections of the radar signal SWOT pulses to Earth's surface. The widely separated antennas give SWOT the resolution to measure the height of a patch of water just kilometers wide, rather than hundreds of kilometers, bringing small eddies into view.

Armed with the precise observations, hydrologists will be able to say how lakes and rivers change seasonally, and how short-term climatic drivers, such as El Niño, affect those rhythms. For marine ecologists, SWOT will be able to chart how the levels of the world's major rivers drop each time a dam or weir interrupts them, and how severely that fragments aquatic habitats. It will also see the ripples that betray a river's shallows and deep pools, a boon to studies of how rivers evolve. And SWOT will capture flood waters as they move down river, which should help flood modelers, although the measurements won't be fast enough to help communities prepare…

SWOT's view of eddies may be its biggest payoff. For example, it will test predictions that thousands of small eddies stir the ocean at any one time, says Sylvia Cole, a

---

[2] Paul Voosen, Science, "NASA mission will study how hidden ocean swirls soak up heat of global warming," Dec 7, 2022, https://www.science.org/content/article/nasa-mission-will-study-hidden-ocean-swirls-soak-heat-global-warming

physical oceanographer at Woods Hole Oceanographic Institution (WHOI). Eddies just a few kilometers across likely play a critical role in stirring heat and carbon into the oceans near the poles, Morrow says. They also drive the mixing in smaller seas, she says. "We're probably underestimating the energy in the Mediterranean by 90% because we're missing these smaller scale structures."

At the coastlines, SWOT will provide a detailed picture of how hot spots of sea level rise in the open ocean influence coastal inundation, says Sönke Dangendorf, a physical oceanographer at Tulane University. It will also study another potential threat to coasts: small eddies that might warm nearby waters, fueling stronger hurricanes, Morrow says. "We're trapping more heat not just at the surface, but also at depth." These are important questions to answer, fast, as much of humanity lives along coasts, she adds. "Everything is felt more keenly in the coastal zone."

4. Other Energy Related Applications

SWOT is a powerful new tool. I believe that it will facilitate major efficiency improvements in energy related applications beyond those that are described above. Some of these are described below.

4.1. Hydropower

The text below is from the source referenced here.[3] A few references in the original text may be also referenced below.

The current management of most hydropower dams in the world is based on rule curves that outline the reservoir storage targets to be met at specific times of the year. These rule curves are designed based on existing storage volumes using a climatology of historical flow observations. Operating strictly based on these rules, without considering recent or near-future changes in inflow patterns, can result in high inefficiency in operating the dam, at least from a hydropower standpoint.[4] Recently, significant research has been carried out on hydropower generation based on short-term inflow forecasts derived from publicly available numerical weather prediction (NWP) models. In these studies, forecast fields from the NWP model of the Global Forecast System (GFS) were used to force a hydrologic model to forecast reservoir inflow for 1-16 days lead-time. The optimization of reservoir operations was performed based on the forecast of inflow. This concept was demonstrated over Detroit dam in Oregon (US), showing that an additional 9,270 MWh of hydropower can be gained during two-year return period storm events. Optimization over a longer ten-month period raised the total energy production by 5.6% over the traditional rule-curve scenario. Such optimization of hydropower dam operations based on weather forecast data can not only increase hydropower generation, but also satisfy the goals of flood control and dam safety. Our research on weather forecast-informed hydropower operations clearly reveals that the current and future inventory of hydropower dams can operate at much higher efficiency

[3] Shahryar Ahmad, Matthew Bonnema and Faisal Hossain, "Generating more hydropower with less dams and better ecosystem outcomes: is it possible?" Dam and WaterPower Magazine, Jan 2020, https://swot.jpl.nasa.gov/system/publications/257_Eco-safe_Hydropower_Op-Ed_in_Dam_and_WaterPower_Magazine_Jan_2020.pdf

[4] Miao, Y., X. Chen and F. Hossain. (2016) Maximizing hydropower generation with numerical modeling of the atmosphere, J. Hydrologic Engineering (ASCE), vol. 21(6), (doi: 10.1061/(ASCE)IR.1943-4774.0001098), https://www.researchgate.net/publication/300080990_Maximizing_Hydropower_Generation_with_Observations_and_Numerical_Modeling_of_the_Atmosphere

levels, thereby requiring less dams to be in operation in order to meet growing energy demands…

Author's comment: It is a no-brainer that SWOT will make hydro-power forecasts much more accurate by measuring reservoir levels, major river inflows and medium-term weather forecasts more accurately and providing data that will make hydrological models more accurate. Also see the next subsection.

4.2. Accurate River Flow Estimation

Surface water storage and fluxes in rivers, lakes, reservoirs, and wetlands are currently poorly observed at global and regional scales, even though they represent major components of the water cycle and impact human societies deeply, both in terms of water resources and catastrophic events, such as floods. In situ networks are heterogeneously distributed in space, and many river basins and most lakes–especially in the developing world and in sparsely populated regions–remain unmonitored. The continental water cycle can be formulated in a simple mass balance equation, linking the total water storage variation in time (ΔS) with different water fluxes between the continental surface, the atmosphere, and the underground domain: These are precipitation (P), evapotranspiration (E), the infiltration in the subsurface (I), and the overland flow (Q). The mass balance equation simply assumes that the total water storage variation, ΔS, is equal to the precipitation, P, from which are subtracted the terms, E, Q, and I. Altimetry products from remote sensing are increasingly used for the monitoring of these hydrological cycle components. Several altimetric satellites have been launched in the past to measure water surface elevations, among which ERS-1 (1991–2000), TOPEX/Poseidon (1992–2006), ERS-2 (1995–2003), Jason-1 (2001–2013), Envisat (2002–2012), Cryosat-2 (2010–now), SARAL (2013–now), Sentinel-3 (2016–now), and Jason-3 (2016–now). They provide repetitive water elevation measurements on a global scale, something which is particularly important for ungauged basins. They do, however, have many limitations, such as a longer revisit time (between 10 and 35 days), and coarse spatial resolution. The instruments' footprints are several square km and they are only observed from their nadir (from the vertical of the satellite). Among them, the CryoSat-2 mission, launched in 2010, offers a very dense spatial sampling pattern with an across-track distance of only 7.5 km, but with a drifting ground track and a full repeat cycle of 369 days. To overcome these limitations, a new satellite mission based on SAR (synthetic aperture radar) interferometry was proposed: This was called WATER (Water and Terrestrial Elevation Recovery), providing water elevation maps for two 50 km swaths [8]. In 2007, the National Research Council recommended this new satellite mission to NASA (The National Aeronautics and Space Administration), under the name SWOT (Surface and Ocean Topography), to measure both the ocean and land water surface topography. This new mission, conjointly developed by NASA, CNES (Centre National d'Etudes Spatiales), CSA/ASC (Canadian Space Agency/Agence Spatiale Canadienne), and UKSA (United-Kindom Space Agency), is planned for launch in 2021 and will observe the whole continental water-estuaries-ocean continuum. SWOT is designed to observe a large fraction of rivers and lakes globally and will provide observations of their seasonal cycles. SWOT will be the first altimetry mission to provide a quasi-global coverage of continental surfaces between 78° S and 78° N. Especially, it is designed to observe big and intermediate (or regional)-scale basins (i.e., 50,000–200,000 km2 drainage area) in 21 days, the duration of a full orbital cycle. Water level measurement errors are expected to be 10 cm aggregating pixels over a 1 km2 water area (e.g., a 10-km reach length for a 100-m-wide river). This offers a new opportunity for the linking of open water surface elevations, land surface *processes, and meteorology more closely on this scale. The SWOT mission will provide relevant information on the temporal evolution of the surface water storage. This information will allow a better understanding of the term, Q, both spatially and temporally, playing an important role in the mass balance equation.*[5]

Author's comment: The referenced paper goes into great detail regarding using SWOT data for a specific river system in France, but my intent is to point out that the much more accurate models developed from SWOT data can be used for much more accurate hydrological water shed and stream forecasts for all water uses, including hydroelectric power, flood management and wildlife services.

Also another element of river-flow is river discharge estimates.

River discharge is a key element of the water cycle, but river gaging networks have significant gaps at the global scale. In 2021, the Surface Water and Ocean Topography (SWOT) mission will collect high-accuracy measurements of the world's surface waters, including all global rivers wider than 100 m. In anticipation of SWOT, methods to estimate discharge from its measurements have been developed but have yet to be tested on real-world data at the spatial scales and accuracies expected of SWOT. We test three such discharge algorithms on data collected by AirSWOT, an airborne variant of SWOT, as it flew over the Willamette River in Oregon, USA. We show that river discharge can be estimated by these algorithms with encouraging accuracy (10–31%) using only airborne measurements and a model-derived estimate of the mean annual discharge. We stress the need for further testing of these algorithms to determine their sensitivities to the initial estimate of flow and the hydraulic character of the river reach but suggest that these results are encouraging for future global-scale deployment of SWOT discharge algorithms.[6]

Measurements of river discharge help quantify the Earth's water, biochemical, and energy cycles and are critical markers of resource use, water scarcity, and global change. Despite considerable efforts to catalogue and aggregate global streamflow records (e.g., the Global Runoff Data Centre), in situ gage data remain unobtainable in many regions of the world due to financial, infrastructural, and political constraints. This leads to a reliance on hydrologic models for filling gaps in gaging networks, and although remote sensing plays an increasingly important role in large-scale studies of the water cycle, methods to estimate streamflow from remote sensing measurements remain under development.

Estimating river discharge in un-gaged basins using space-borne remote sensing measurements requires solving under-constrained problems with noisy, temporally discontinuous data. Remote sensing estimates of discharge typically utilize radar altimetry to measure elevations, imagery data to measure width or inundation extent, or a combination of the two. If these measurements can be made concurrently—that is, if the free surface of a river can be fully mapped in two dimensions—discharge can be calculated using open-channel flow equations with relatively few unknown parameters,

[5] Vincent Häfliger, Eric Martin, Aaron Boone, Sophie Ricci and Sylvain Biancamaria, MDPI, "Assimilation of Synthetic SWOT River Depths in a Regional Hydrometeorological Model," Jan 4, 2019, https://www.mdpi.com/2073-4441/11/1/78

[6] S. Tuozzolo, G. Lind, B. Overstreet, J. Mangano, M. Fonstad, M. Hagemann, R. P. M. Frasson, K. Larnier, P.-A. Garambois, J. Monnier, M. Durand, American Geophysical Union, Geophysical Research Letters, "Estimating River Discharge With Swath Altimetry: A Proof of Concept Using AirSWOT Observations," Jen 18, 2019, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018GL080771

and floodplain flows can be better characterized in gaged and un-gaged contexts. The Surface Water and Ocean Topography (SWOT) satellite mission launched recently and will generate two-dimensional maps of water surface elevation and extent using Ka-band interferometric synthetic aperture radar (inSAR) on a 21-day orbit, creating multi-temporal data sets of unprecedented accuracy (10-cm elevation root-mean-square error (RMSE) for 1-km2 areas) and resolution (10- to 70-m pixel resolution) for the world's inland and oceanic waters.

In anticipation of SWOT, river discharge algorithms which invert flow law equations for unobserved hydraulic parameters are under development. SWOT's measurements will generate time-varying elevation, width, and slope data but will not measure the channel bathymetry below the lowest flow observed by SWOT or the hydraulic resistance to flow, two essential parameters in open-channel flow equations. To solve for these unknown values with no in situ data, prospective SWOT discharge algorithms use a variety of numerical and statistical approaches, which have been developed and tested using synthetic and real-world data sets. However, algorithms have yet to be tested on SWOT-like data from remote sensing platforms, and key questions around expected algorithm accuracies remain unanswered. If these algorithms can provide reliable and robust estimates of periodic river discharge across all SWOT reaches, they will fill substantial gaps in global data records of river discharge and runoff and will serve important roles in improving and updating global hydrologic and hydrodynamic models.

Testing algorithms using real-world data is crucial for better understanding their limitations, development needs, and applicability, and the AirSWOT instrument is well suited for pre-SWOT algorithm testing. AirSWOT is an airborne variant of the SWOT instrument, which has been developed and deployed in advance of SWOT for algorithm development and prototyping and will be used as a calibration/validation tool when SWOT is launched. The AirSWOT payload includes a Ka-band radar interferometer and an optical camera; while the Ka-band instrument on AirSWOT uses the same interferometric techniques as SWOT, the flight elevation and view geometry necessary for wide-swath observations from an airborne instrument leads to distinct phenomenological and error characteristics. Altenau et al. recently showed that AirSWOT can map water surfaces over a 90-km section of river, close to the scale of a SWOT swath, with water surface elevation and slope RMSEs of 9 cm for 1-km2 averaging areas and 1 cm/km for 10-km reaches, which matches or exceeds expected SWOT accuracies and suggests it will be a valuable tool for SWOT calibration and validation…

These first discharge algorithm inversions on Ka-band airborne inSAR data show that SWOT discharge algorithms can provide reasonable estimates of discharge on real-world, remotely sensed data when in situ information is absent, offering a preview of the broader promise of SWOT. Limitations of the AirSWOT data set, including the limited number of observations and lack of width data due to clouds, highlight the difficulty of generating and evaluating real-world SWOT-like data prior to mission launch. Further work with AirSWOT and similar data sets is needed to evaluate the robustness of algorithms to variable flow conditions, sampling intervals, and measurement uncertainties. In particular, algorithm sensitivity to the prior estimate of discharge stands out as an important qualifier to otherwise encouraging results in this study and necessitates additional investigation in future algorithm test studies.