NASA Science Mission Directorate
Research Opportunities in Space and Earth Sciences – 2019 NNH19ZDA001N-SWOTST
A.12 Surface Water and Ocean Topography (SWOT) Science Team

This program element selected members for the NASA Surface Water and Ocean Topography (SWOT) Science Team. The primary goal of the current SWOT Science Team is to assist with pre-launch mission planning and conduct immediate post-launch scientific exploitation of the SWOT data in the fields of physical oceanography, hydrology, and synergistic sciences. NASA received 68 proposals and selected 17 with funding of ~$12M over four years.

Brian Arbic/University of Michigan, Ann Arbor
Predictability of Stationary and Non-Stationary Internal Tides in the US Navy Global Hydrodynamical Model
19-SWOTST19-0025

A group of US scientists proposes to examine the predictability of stationary and non-stationary internal tides in the US Navy global hydrodynamical system. The system is built upon 1/12.5 and 1/25 degree global simulations of the HYbrid Coordinate Ocean Model (HYCOM), for which atmospheric and tidal forcing are simultaneously included. The HYCOM simulations therefore carry the general circulation, mesoscale eddies, barotropic tides, internal tides and other internal gravity waves (IGWs) including internal tides, all at once. Through interactions with eddies and temporally varying stratification, a substantial fraction of the internal tide variance is non-stationary. The prediction system includes the Navy Coupled Ocean Data Assimilation (NCODA) scheme, which places mesoscale eddies in their correct locations based on assimilated altimeter data, and provides a more accurate background stratification. The accuracy of the HYCOM barotropic tides is improved through an Augmented State Ensemble Kalman Filter (ASEnKF), which sorts through a set of perturbations with horizontal length scales reminiscent of open-ocean tides to find an optimal correction to the forcing. We therefore have all the ingredients in place to test the accuracy of the model in predicting stationary and non-stationary internal tides. The model already predicts up to 69% of the stationary internal tide sea surface height (SSH) variance in some internal tide hotspot regions. We expect that number to increase as we improve the ASEnKF with additional perturbations focused on regions of large resonant coastal tides, that have smaller horizontal scales resembling those of the coastal tides. Preliminary results with a relatively small number of coastal perturbations show some degree of improvement in our modeled barotropic tides. An additional improvement to our model is likely to come from assimilation of SWOT data itself, which will provide a much greater density of observations than nadir altimetry.

We will test the modeled stationary internal tides against nadir and SWOT altimeter results. The modeled non-stationary internal tides will be tested through a variance reduction exercise—we will determine whether nadir and SWOT SSH variance in the

semidiurnal band is reduced when corrected for by our semidiurnal band-passed SSH. The correction of non-stationary internal tides has been put forth by ourselves and others as a “grand challenge” for the SWOT project. Even if global hydrodynamical models are not able to successfully predict non-stationary internal tides, we will learn a lot from the attempt. The proposed work is relevant to the SWOT solicitation because internal tides and gravity waves will represent a substantial signal in SWOT, and one that must be corrected for if smaller-scale low-frequency motions such as mesoscale and submesoscale eddies are to be clearly seen in SWOT observations.

We will hire a postdoc at the University of Michigan to perform these tests of HYCOM skill in modeling internal tides. The postdoc will also feed global SSH output, and three-dimensional output in the SWOT Cal/Val region, from HYCOM to the project. In addition, funds for this project will support co-Is to help with improvements in the ASEnKF, subsample a 1/50 degree North Atlantic HYCOM simulation to quantify the effects of the coarser resolution in our operational systems, and explore what happens to our hydrostatic model in regions where strongly nonhydrostatic internal solitons develop in the actual ocean. Finally, we will leverage other funding to continue our work in quantifying the accuracy of internal tides and the internal gravity wave continuum in several community global hydrodynamical internal wave models, which in recent years have become of growing importance for the SWOT mission.

Joern Callies/California Institute of Technology
Understanding the Spectral Content of SWOT's Sea Surface Height Data
19-SWOTST19-0017

The sea surface height maps returned from the SWOT spacecraft will contain signals from both geostrophic turbulence and internal tides. Any dynamical interpretation of such maps therefore requires us to distinguish between signals arising from these drastically different types of motion. We here propose to apply in-swath wavenumber–frequency spectral analysis to distinguish between and characterize these two types of motion. The distinction will be based on the narrowband nature of internal tides, yet the analysis will be general enough to also allow for the discovery and characterization of unexpected signals.

The proposed work consists of two parts. First, we will generate expectations for SWOT spectra using theoretical calculations, existing observations, and high-resolution simulation data. We will study the recoverable spectral signals given SWOT’s spatial and temporal sampling pattern consisting of 50 km wide swaths and a 1-day or 21-day repeat cycle. Second, in light of these expectations, we will estimate and interpret spectra from data obtained in the fast-sampling phase of the SWOT mission. We will perform an early assessment of whether the geostrophic signal at meso- and submesoscales is consistent with recent theories and models of submesoscale dynamics and mesoscale–submesoscale energy exchange.

We propose to take full advantage of the early SWOT data by calculating two-dimensional wavenumber spectra from the in-swath SSH fields. This has the conceptual and practical advantage that it extracts the maximum amount of spectral information, without having to apply and optimize any spatial mapping or averaging prior to the analysis. The spectral signature of noise is particularly simple in this framework.

We will distinguish between tidal and geostrophic signals using wavenumber–frequency spectra. This has the advantage that we can make use of the spectral concentration of tidal variance around both alias frequencies and modal wavenumbers, allowing a more robust identification of tidal signals than is possible in methods operating the frequency or wavenumber domain alone. Knowledge of the sampling pattern enables us to calculate exactly what spectrum to expect for a narrowband signal, which facilitates the characterization of internal-tide signals and the identification of deviations from the narrowband null hypothesis. Notably, the proposed spectral analysis captures not only the component of internal tides that is perfectly phase-locked to the astronomical forcing: slow phase shifts broaden tidal peaks somewhat but leave them identifiable as distinct peaks.

We expect the proposed spectral analysis to yield a basic dynamical characterization of the signals captured by SWOT. This will allow direct insight into the dynamical theories of meso- and submesoscale turbulence, and it will provide new observational constraints for high-resolution numerical simulations. It can also be the basis for further filtering and smoothing of SWOT data.

Kyla Drushka/University of Washington, Seattle
Design and Coordination of SWOT-Related Field Campaigns
19-SWOTST19-0008

SWOT will allow us to observe, for the first time, the 2-D structure of sea surface height (SSH) on ~15-120 km wavelength scales, and has the potential to transform our understanding of ocean dynamics on these scales. Following its launch in 2021 (or 2022), SWOT will spend 90 days in a “fast-sampling phase”, when it will cover a limited set of ground-tracks once per day: at several dozen locations, the satellite will cross over the same place twice per day. The fast-sampling phase of SWOT represents a unique opportunity to capture the rapidly-evolving SSH variability at the small end of the mesoscale (10s of kilometers).

In situ observations will be highly complementary to the SWOT measurements made during the fast-sampling phase for several reasons: to produce a more coherent picture of the surface and subsurface dynamics that generate the SSH signals that SWOT samples; to fill in observational gaps (on shorter time/space scales than SWOT will sample); as ground-truth; and to quantify the oceanographic signals that will affect SWOT measurement noise (e.g., wind, surface waves and currents). Field campaigns during the fast-sampling phase have the potential to add enormous value to SWOT; however, realizing this potential will require community organization and development of a well-

founded basis for experiments with input from the modeling, observational, and SWOT communities.

A number of SWOT-related field campaigns are planned for the fast-sampling period, notably as part of the “Adopt-a-Crossover” (AdAC) effort that has been established to encourage international groups to make in situ measurements within the regions that will be sampled by SWOT during the fast-sampling phase. However, coordination between the AdAC groups is not formalized. A set of guidelines for crossover measurements has not been established and it is unclear which sampling strategies are optimal for making these measurements. The proposed work is motivated by the need for planning and coordination of the field campaigns during the SWOT fast-sampling phase in order to generate datasets that are consistent, accessible, and beneficial to the SWOT mission and science goals. To that end, we have two major objectives:

1) Identify key measurements that should be made as part of SWOT-related field campaigns.

2) Facilitate communication and coordination between groups planning SWOT-related field experiments, and provide a link between these groups and the SWOT Science Team.

The first objective will be carried out by running Observing System Simulation Experiments (OSSEs) based on a set of existing and underway simulations including the so-called MITgcm llc4320 simulation. We will develop a set of recommendations about which measurements, on which scales, from which platforms, would be the most complementary to the SWOT program. For the second objective, our team will enable communication and coordination between groups planning fieldwork. We will facilitate the implementation of strategies developed in Objective 1, organize telecons and in-person meetings, help make resources and data consistent and accessible, and liaise with the greater SWOT Science Team. This project will be carried out in collaboration with the French group led by Francisco d’Ovidio (who has submitted a related proposal to TOSCA).

Michael Durand/Ohio State University
Comprehensive Evaluation of the SWOT Discharge Data Product: What Will We Learn About the World’s Rivers?
19-SWOTST19-0055

The Surface Water and Ocean Topography (SWOT) mission will measure river height, width, and slope globally for rivers wider than 100 m. River discharge will be computed using simple flow laws via a combination of SWOT measurements, and unmeasured “parameters” such as river bathymetry and friction coefficient. The Science Requirement Document specifies that the Science Team in place during the SWOT mission compute the flow law parameters offline from the SWOT mission operations, and that discharge uncertainty estimates be made available. The Discharge Algorithm Working Group (DAWG) of the 2016-2020 Science Team has defined discharge algorithms and

integrators in order to fulfill this purpose. The DAWG has also specified that two data products be created: one constrained by in situ streamflow gages, and the other unconstrained by gages. Our partner proposal (led by Colin Gleason, University of Massachusetts) will (if funded) undertake the computational effort to compute these parameters using a newly developed computational environment known as “Confluence”. Here we propose to do three things.

First, we will contribute new components to Confluence needed for full functionality, including a comprehensive uncertainty model. The DAWG has recommended that the official gage-constrained and gage-unconstrained discharge data products be computed as a consensus among several discharge algorithms and integrators developed independently by multiple research groups and tested as part of DAWG activities. We propose to do the necessary work to determine the optimal way to produce a consensus discharge estimate and discharge uncertainty estimate for SWOT mission operations. We will compare two candidate consensus algorithms, and work with the DAWG to select the optimal approach. We also propose a candidate for comprehensive discharge uncertainty budget for each algorithm, and for the consensus algorithms. We will test, implement, and work to see the optimal methods deployed for SWOT mission operations.

Second, we will comprehensively evaluate the SWOT discharge accuracy, as well as the discharge uncertainty estimates, working with datasets compiled by the SWOT Calibration/Validation team. As we expect discharge accuracy to vary across reaches, we here propose a set of classes for global river reaches, on which to stratify discharge accuracy analyses. The discharge uncertainty estimate data product is a critical complement to the discharge estimates themselves. We will assess discharge uncertainty estimates across a range of rivers, to ensure users have information about discharge accuracy. Finally, we will perform quality control of all discharge parameters computed by Confluence before these are written to a database and delivered to the SWOT project for use in mission operations.

Third, we will quantify the overall improvement in global knowledge of streamflow due to SWOT discharge data products. We will assess the extent to which SWOT river discharge improves upon global knowledge of discharge available by information external to SWOT, exemplified by hydrological models. We will compare the gage-constrained and gage-unconstrained data products to calibrated and uncalibrated global hydrological models, respectively. We will use SWOT discharge and its uncertainty to characterize and present the first ever global distribution of river discharge computed directly from river observations.

Sarah Gille/University of California, San Diego
Regional Ocean State Estimation for SWOT: Resolving Variability in the California Current System

19-SWOTST19-0027

We aim to develop an ocean state estimate constrained by data from the Surface Water and Ocean Topography (SWOT) satellite. This product will be used to probe the physics governing oceanic variability in the California Current System (CCS), both during the SWOT calibration and validation (cal/val) time period and throughout the operational SWOT mission. SWOT will measure ocean sea surface height at 2 km spacing within parallel 50-km-wide swaths, albeit with significant spatial and temporal gaps. High-resolution assimilating ocean models offer one strategy for studying the O(10 km) processes resolved by SWOT, while bridging the spatio-temporal gaps between satellite observations. Our group's ongoing contributions to the SWOT science team have been directed toward developing 4-dimensional variational (4dVar) assimilation for SWOT, using the MITgcm. The strength of 4dVar is that the state estimate, while constrained by data, is governed by the time-varying physics, without unphysical corrections. This is particularly valuable for SWOT as the dynamics we target can evolve rapidly but have the potential to be skillfully modeled. Our strategy has two themes: (1) accurately modeling dynamics at O(10 km) and greater, and (2) extending the duration of the 4dVar assimilation window used for processes with scales of O(10 km). For both we focus on the CCS, which is historically well sampled and which has been targeted for supplemental observations as part of SWOT cal/val.

Theme 1: Large-scale oceanic motions are largely geostrophic, but at SWOT resolutions ageostrophic processes can be more energetic than geostrophic motions. To address the ageostrophic components of the flow, we have been developing strategies for modeling and analyzing the sea surface height contributions from surface gravity waves, baroclinic tides, and internal waves. Assimilating signals at the scales that SWOT will observe is prohibitively expensive in a global domain, and we aim to construct regional state estimates with carefully defined open ocean boundary conditions. Recent findings have demonstrated that internal waves propagate long distances across ocean basins to inject significant amounts of energy into the CCS. Traditional regional model boundary conditions do not permit internal wave energy to enter through open boundaries. Assimilation strategies for SWOT will require a more sophisticated open boundary, capable of fluxing internal wave energy into the regional model domain. One proposed goal is to determine best practices for prescribing these open boundary conditions. Our model, which includes tides and has sufficient resolution to support internal wave propagation, will provide a dynamically consistent framework for analyzing the internal wave contribution to overall ocean energetics and for assessing the physical processes governing upper-ocean mixing, vertical velocity, and the sea surface height signal measured by SWOT. The inclusion of surface gravity waves in our model will allow us to explore strategies to mitigate SWOT retrieval biases associated with surface waves.

Theme 2: State estimation via 4dvar utilizes the adjoint of the forward model to systematically solve for the model inputs that give a trajectory best fitting the observations. The adjoint model loses skill on the timescale at which nonlinearities dominate the solution. For O(100km) dynamics in the CCS this occurs on timescales of approximately 3 months. However for the O(10km) dynamics that we are targeting, this

occurs more rapidly. We propose to determine this predictability timescale, which may be shorter than the ~21 day SWOT repeat and to explore ways to extend this assimilation window duration by adding control parameters into the window. Demonstrating state estimation capabilities for high-resolution processes and providing a formal means to map the SWOT data lays the foundation for future regional state estimates and for high-resolution global state estimation.

Colin Gleason/University of Massachusetts, Amherst
Developing, Testing, and Operationalizing a Cloud-Based Open-Source System to Produce a Global SWOT Discharge Product and Advance the Science of Discharge Estimation
19-SWOTST19-0018

We propose to develop, implement, and maintain a cloud-based, open-source software system capable of producing the parameters needed by NASA for the official discharge product for every river in the SWOT River Database (SWORD). We name this system Confluence, as it represents a merging of a decade of previous theoretical work, SWOT data, Science Team (ST) products, and an ST community approach to estimating discharge. Confluence will deploy five Mass conserved Flow Law Inversion (McFLI) discharge algorithms developed by the previous ST at the global scale. We will add numerous and necessary novel diagnostics pre- and post-McFLI, combine McFLI algorithms into a consensus product, include evaluation modules, and provide discharge parameters to the ST and to NASA. We anticipate additional inputs of prior data from other ST members that will improve our discharge estimates and thus the discharge product. Our discharge output will also be readily available to the ST as inputs for other projects seeking to merge SWOT discharge with models. In sum, we are seeking to provide the computational backbone of SWOT discharge for JPL and the entire ST, consistent with the call for exactly such proposals.

Creating our proposed system is a substantial undertaking, and in order to “fully develop and distribute any proposed data products using proposed resources,” we believe that developing, testing, and distributing a global discharge product will occupy the entirety of the pre-launch period and require a substantial percentage of total proposed resources, leaving little time pre-launch for the science of discharge. This is grounded in our experience developing a working prototype of Confluence over the past calendar year. We will thus partner with an ST proposal submitted by Michael Durand of The Ohio State University, who (if funded) will develop a select few novel Confluence modules and lead discharge evaluation pre- and post-launch, tasks beyond available resources for this proposal. Also following our prototype experience, we will hire a dedicated software engineer for this pre-launch period to professionally develop the software on time and on budget. The software engineer will also optimize existing McFLI algorithms, hopefully leading to large gains in computing speed.

Post-launch (and post-software development), we are motivated by a driving science question: “what is the best way to combine prior databases and SWOT observations to

estimate global river discharge?" The computer engineering personnel herein are experts in machine learning and big data for infrastructure and environmental systems. Confluence will have access to all global SWOT data, a rich database of prior information from the ST, and numerous discharge estimates from different physical inversion platforms: an unprecedented volume of data. Thus, our computer engineering expertise will be brought to bear to assess whether the wealth of global SWOT data collated in Confluence could more effectively estimate discharge using machine learning techniques rather than with McFLI as envisioned by hydrologists during the past decade of SWOT theory work by the ST.

We ultimately propose to be the 'final stop' for all information needed to produce discharge at the global scale. We hope to provide a platform to amalgamate all ST discharge knowledge and insight into an efficient, open source, and comprehensive software platform. Having this single software system will prevent redundancies, improve efficiency, and ensure the best discharge product possible is delivered on time to NASA and the public. Our open source and containerized software can run on any operating system, cluster, or cloud, and thus individual ST members, NASA, and the public can pursue their own discharge goals on their own terms while we, at the same time, deliver on mission discharge requirements at the global scale.

Dennis Lettenmaier/University of California, Los Angeles
Development of Spatiotemporally Continuous Runoff using SWOT Discharge Data Products
19-SWOTST19-0062

Traditionally, spatially distributed hydrologic models are calibrated using stream gauge (point) measurements of river discharge (streamflow). The hydrologic model calculates runoff, and the runoff is converted to discharge at the gauge location using a postprocessor that routes runoff through a representation of the channel network. Then, hydrologic model parameters, such as soil characteristics, are adjusted to minimize errors between modeled and measured discharge. Because the calibration is performed on a stream-gauge by stream-gauge basis, this method results in discontinuities in parameter values (and hence, model-derived fluxes and states) at watershed boundaries. Furthermore, this calibration approach is not adaptable to un-gauged basins. We propose an alternative pathway for implementation of SWOT data in hydrologic models in which runoff (as contrasted with streamflow) is estimated via a two-step process from SWOT spatially distributed hydrologic observations. The first step is assimilation of SWOT observables into an assimilation system whose dynamical core contains elements of both hydrologic and hydrodynamic models. The resulting streamflow estimates then will be ingested into an algorithm known as Inverse Streamflow Routing (ISR), which will produce spatially distributed runoff. We will develop and test the method using synthetic SWOT data (produced, as in our earlier work, using the SWOT instrument simulator), as well as SWOT observations as they become available. We will apply the method to large river basins and smaller sub-basins within them, both within the conterminous U.S. (where relatively abundant hydrologic data will assist us in methods development) and to

large river basins globally, where data are sparser, but the incremental payoff in terms of hydrologic prediction using SWOT data is greater. Our project will address two research questions that are central to the widespread use of SWOT data for hydrologic prediction: How can SWOT observables best be used to derive spatially and temporally continuous estimates of land surface runoff? and With what accuracy can SWOT-derived runoff products, used in conjunction with current-generation hydrologic models, predict the dynamics of streamflow in un-gauged river basins? The work we propose directly responds to research priorities set forth in the NRA and the SWOT Science Description Document. Specifically, the project will directly address core SWOT science question What is the spatial distribution of freshwater storage and runoff through rivers, lakes, and reservoirs? (area 2.2.1 of the solicitation) and research area 2.2.2 of the solicitation Development and implementation of algorithms to produce river discharge estimates from SWOT data globally. The hydrologic model parameters that can be estimated using SWOT-derived runoff directly are expected to improve the performance of current model simulations across a range of space-time scales. Because streamflow (rather than runoff) is typically observed at gauges that represent upstream drainage areas (typically 100s of km2 and larger) water balance studies typically have an inherent spatial scale that is linked with these drainage areas. This is so even though coupled land-atmosphere models (and increasingly, off-line simulations) are performed at different spatial scales (grid cell sizes). Our work will help to bridge this gap and will facilitate production of SWOT-based runoff data products appropriate to grid-based models in un-gauged or under-gauged areas where current measurements are inadequate for making useful hydrologic inferences. This will help enhance our understanding of the hydrologic processes in these remote regions, which aligns well with the SWOT science requirement to make fundamental advances in the understanding of the spatial and temporal distribution of the storage and discharge of water on land.

Eric Leuliette/National Oceanic and Atmospheric Administration
Investigating Operational Applications of SWOT
19-SWOTST19-0033

NOAA uses satellite radar altimetry data to supply sea surface heights, waves, and surface wind speeds to a wide range of operational users. Nadir altimetry is supplied directly to forecasters in the Ocean Prediction Center, assimilated into operational ocean models, and processed into products like ocean heat content. Altimetry is critical for tropical cyclone intensity forecasting and safe navigation. As wide-swath altimetry matures, there will be several challenges to reconstruct regular two-dimensional fields of sea surface height to be suitable for use in NOAA applications. We propose to study new techniques to create high-level data products in U.S. coastal regions from SWOT and the nadir altimeter constellation.

Dimitris Menemenlis/Jet Propulsion Laboratory
Diagnosis of Air-Sea Momentum and Heat Fluxes Using SWOT

19-SWOTST19-0070

Background:
The high spatial resolution (15 km wavelength) and wide swath (120 km) of the upcoming SWOT observations will permit, not only a much better estimation of ocean kinetic energy, but also the diagnosis of kinetic energy exchanges between scales and of the vertical velocity field in the first 500 m below the surface. These quantities are crucial to accurately assess the ocean dynamics impacts on physical-biological interactions, dispersion of tracer and pollutants, heat and carbon transport, and on weather prediction. The methodologies that are being developed to diagnose these quantities from SWOT observations are presently based on ocean general circulation models (OGCMs) or on ocean data assimilation (ODA). The common parameterization used in these models is such that wind forcing acts as an eddy killer, decreasing the ocean eddy kinetic energy by ~30% (Eden and Dietze 2009). However, a number of studies carried out during the last two to three years using coupled ocean-atmosphere models, strongly challenge this eddy killer paradigm. We now know that mesoscale eddies and submesocale structures impact the atmosphere and, in particular, the local wind speed over oceanic eddies. The resulting wind feedback on the ocean, not taken into account in “forced” OGCMs or ODA results, leads to a much smaller (~< 10% as opposed to 30%), region-dependent eddy killer effect. Some preliminary results using a mesoscale-eddy-admitting global ocean-atmosphere model confirms these findings, making these eddies and their associated SSH much more energetic than in forced OGCMs. These new results question the adequacy of forced OGCMs and ODA results for anticipating and interpreting SWOT SSH observations.

Proposed work:
The present proposal aims to revisit the characteristics of the oceanic mesoscale and submesoscale turbulence in the world ocean when the full atmospheric feedback on mesoscale eddies is taken into account. This will be done using a new, groundbreaking global ocean-atmosphere model, which will be integrated with horizontal grid spacing of 1–3 km. More precisely, we will use a suite of numerical experiments involving coupled and uncoupled atmospheric and oceanic models to diagnose the wind-induced killer effect on both mesoscale eddies and submesoscale structures. Our numerical results will provide predictions for processes to be observed by the SWOT Cal/Val and S-Mode experiments. We further intend to develop a parameterization of the atmospheric feedback on eddies, to be used in forced models, that takes into account the impact of ocean currents on the wind stress curl and divergence (Tanaka and Schneider, 2017). This parameterization will be used to better represent the eddy killer effect in forced models and may also be used in weather forecast models to take into account the impact of mesoscale eddies on the wind field using SWOT observations.

Significance to the objectives of NASA programs:
The expected numerical results will provide new guidelines for analyzing observations from the upcoming SWOT mission. Comparison of our numerical results with SWOT observations and high-resolution in-situ observations will lead to a better understanding and quantification of ocean dynamics and of the coupled ocean-atmosphere system.

Richard Ray/Goddard Space Flight Center
Barotropic and Baroclinic Tide Models for and from SWOT
19-SWOTST19-0021

Under current support our group has developed a series of new barotropic and baroclinic tide models to support the SWOT mission. These have been made available to the SWOT project, and we expect a number of refinements to be implemented before launch. Part of these refinements will exploit the wealth of new altimeter data now being collected from a large fleet of NASA and non-NASA satellites, especially data from Cryosat-2, which is proving extremely useful for tidal applications. Extensive refinements are expected once SWOT data are collected during the latter half of this proposed investigation.

For barotropic tide models, our immediate goal is to deliver updated models to the SWOT project in time for the project's initial processing of real SWOT data. These updated models already improve tide prediction in polar regions relative to all other existing global models. Afterwards, pre-launch work will continue to focus on both polar and coastal regions. Some refinements in our processing of CryoSat-2, whose time series continues to grow, are planned (e.g., better removal of outliers from sea ice). We plan to begin incorporating new data from ICESat-2, whose small footprint has advantages for extracting sea level from small leads in ice-covered water. We have found that tidal analysis of GRACE range-rate data provides a valuable and unique method to highlight inaccuracies in polar tide models, and we will continue to use these data.

Most of our proposal, however, is devoted to baroclinic tides, both coherent and incoherent. For the coherent internal tide, our group has developed three altimeter-constrained models, using very different techniques, with one (model HRET8.1) selected to provide internal tide ""corrections"" in future GDR-F altimeter products. All of these models will be improved, in ways we outline, by both refinements in methodology and by continued incorporation of more data, including eventual incorporation of SWOT data.

Co-I Kelly has also developed an efficient, unconstrained, high-resolution model that is ideal for testing sensitivity to bathymetry, background currents, stratification, and dissipation. Moreover, a mechanism exists for inverting for such effects by fitting to our data-constrained models. By such fine tuning, we anticipate that the model will prove capable of removing tidal variance, both coherent and incoherent, from SWOT data.

The model, as well as the HYCOM model being run by our colleagues Brian Arbic and Jay Shriver, will also be used to generate simulations we require for a separate purpose. We have developed a new approach to extract incoherent internal tides in SWOT data based on using special principal-component basis functions derived from analysis of unconstrained models, with initial work using HYCOM outputs. This method looks encouraging in an early implementation, clearly capable of removing coherent and incoherent internal-tide energy in HYCOM data sampled via the SWOT Simulator. The

method will be much extended during our new investigation, as spatial and temporal windows are optimized for each class of altimeter (nadir and swath), and subsequently applied to both 1-day and 21-day SWOT data.

We anticipate the SWOT 1-day repeat data will be a remarkably valuable new resource for the study of tides and other high-frequency variability, and we plan to devote extensive efforts to the analysis of these data, now expected to be collected during early 2022. With 7 full cycles of the (aliased) M2 tide sampled over the 90-day campaign, the data are ideal for testing current models. Moreover, since several studies suggest internal tide variability has temporal decorrelation scales of order 15 days, such variability should be detectable. The tidal fields promise unique insights not available during the primary mission.

Ernesto Rodriguez/Jet Propulsion Laboratory
SWOT Discharge Estimation for Multichannel Rivers
19-SWOTST19-0020

Global estimation of river discharge is one of the primary goals of the SWOT mission. We propose to extend SWOT global discharge algorithms developed by the SWOT Discharge Algorithm Working Group (DAWG) to include algorithms especially tailored for multichannel rivers: anabranching, including anastomosing, and braided rivers. Multichannel rivers are common globally, and include some of the world's major rivers: e.g., the Brahmaputra-Jamuna or Solimões Rivers. We will extend existing algorithms, which work with reach-averaged hydraulic variables, to include geomorphic information, such as sinuosity or other braiding indexes, that are defined at reach-level. A product from our work will be a global braiding index database, to be produced prior to launch using existing data, and updated post-launch using SWOT data. The database will enhance the Global River Width from Landsat (GRWL) dataset used by the SWOT science team, and will be of use to the general hydrology community. We will update the Manning discharge relation to include braiding parameters, extending work in the current SWOT science team, which generalized the Manning equation to include subreach variability, resulting in an equation that could be used for reach-level discharge estimation. This generalized discharge relation will then be used, in conjunction with prior braiding parameters, as a basis for a Mass conserved Flow Law Inversion (McFLI) algorithm, extending previous work on the MetroMan and other algorithms to include the updated discharge relation and the use of prior information in the braiding index database. The updated discharge relations and discharge estimation algorithms will be tested prior to launch using calibrated hydraulic models of multichannel rivers. After launch, the algorithm will be demonstrated on the US/Canadian SWOT Cal/Val sites, including the Tanana and Willamette rivers. In collaboration with foreign partners, it will also be tested in the Maroni (French Guyana), Rio Negro (Brazil), Congo (DR Congo), Niger (Mali), Ganges (India/Bangladesh), and Meta (Colombia) rivers. After post-launch algorithm refinement, we will work with the SWOT DAWG to incorporate the algorithm in the operational river discharge data stream to improve the accuracy of SWOT discharge data over multichannel rivers. We expect that the work proposed here will

impact the assessment of global discharge, one of the primary SWOT goals, improve regional discharge estimates that will enhance other science studies, and be useful for river managers as a near real-time estimate of discharge.

David Sandwell/University of California, San Diego
Participation in the SWOT Science Team: Marine Geophysics
19-SWOTST19-0037

We propose to work with SWOT scientists and engineers to optimize the scientific payoff of the mission through pre-launch planning and immediate post-launch exploitation. Our contribution would come in three main areas.

1) We will continue to refine ocean gravity and bathymetry models using conventional radar altimetry and early SWOT data. Our analysis will focus on the large amplitude, short wavelength (6-40 km) gravity signals. Working in this band will help the science community to understand the small spatial scale errors in the SWOT measurements.
2) We will collaborate with CNES/CLS to make the best possible mean sea surface height (MSS) model having both long-wavelength accuracy and high spatial resolution. CLS will contribute the long-term average sea surface height along the repeating tracks of the Topex/Jason series and the ERS/Envisat/SARAL/AltiKa series. SIO will contribute the along-track sea surface slope data from the non-repeat altimeters to fill the gaps between the repeat tracks (see letter of collaboration). The combined model will provide a reference surface for extracting oceanographic signals early in the SWOT mission.
3) We will interpret and model the small scale variations in the gravity field derived from SWOT and other altimeters to improve our understanding of marine geophysics (e.g., abyssal fabric and the global distribution of small seamounts). This will include the production of a global predicted depth grid at 15 arcsecond resolution.

Over the past two decades our group has worked with raw radar waveform data from Geosat, ERS-1, Topex, Jason-1/2, Envisat, CryoSat-2, and SARAL/AltiKa to reduce the small spatial scale noise in the altimeter range measurements due to altimeter bandwidth limitations and ocean waves. In addition, we have significant expertise in interferometric processing of SAR data for extracting crustal deformation from raw radar echoes and orbital data (http://topex.ucsd.edu/gmtsar).
Our 4-year budget will include funding for travel to participate in the SWOT Team meetings as well as support for a SIO graduate student.

Marc Simard/Jet Propulsion Laboratory
Deltas and Estuaries: The SWOT Revolution

19-SWOTST19-0067

Estuaries facilitate the transport of pollutants, sediments, and major nutrients such as carbon, from the terrestrial to the marine environment. The magnitude of its fluxes controls global carbon cycling dynamics and play a regulatory role in biological and physical processes from river headwaters to mouths, and beyond, in coastal and marine systems. Hence, a direct long-term quantification of river discharge is needed to better understand and predict the spatiotemporal dynamics of material transported across the land-sea continuum and the potential effects that may arise from climate and anthropogenic changes. We expect the near-comprehensive and frequent water surface elevation coverage of SWOT will revolutionize our understanding of coastal deltas and estuaries, globally. However, these highly dynamic and spatially complex systems offer methodological challenges that must be addressed prior to SWOT launch.

The goal of this proposed project is to advance SWOT capabilities in deltas and estuaries. As such, we propose to develop and evaluate algorithms to generate SWOT products specific to deltas and estuaries. This proposal is divided into the following specific objectives:

1. Generate a set of detailed spatio-temporal base-maps of coastal deltas and estuaries to support SWOT retrieval of water surface elevation and slope.
2. Improve accuracy of SWOT estimation of water surface elevation and slope in deltaic and estuarine environments.
3. Evaluate methods for reconstruction of tidal signal using SWOT data.
4. Explore the use of ancillary spaceborne remote sensing datasets.
5. Process and evaluate the performance of SWOT in three coastal regions.
6. Generate global water surface elevation and slope for coastal deltas and estuaries.

Our approach considers the global context of SWOT while leveraging the continued progress in hydrodynamic modeling the Mississippi River Delta region, the St. Lawrence and the Seine Estuaries. Until the launch of SWOT expected in 2022, we propose to use these models to 1) evaluate our proposed spatiotemporally adaptive object-based algorithm to increase SWOT retrievals accuracy, and 2) evaluate algorithms for tidal signal reconstruction.

The spatiotemporally adaptive object-based algorithm uses ancillary data to anticipate the impact of layover and account for time-dependent effects from seasonal discharge and/or vegetation growth. Data from SWOT's point cloud are mapped—and averaged—into predetermined water surface objects designed to improve accuracy of water surface elevation. Once evaluated, we use this algorithm to process the real SWOT data and generate water surface elevation and slope in global deltas and estuaries. But given the predominant impact of tides and its role in controlling discharge, slope may not be the best determinant for discharge. Thus, we go further and evaluate new data-driven empirical approaches to reconstruct continuous tidal signals from temporally sparse satellite data (e.g. SWOT) based on regression methods. Again, we use SWOT simulations as a baseline dataset to evaluate the reconstruction methods performance in these three regions. A new method assessment with real SWOT data will be performed

once they become available. We also deliver an assessment of SWOT complementarity with other remote sensing datasets (Sentinel-2, Landsat 8, NISAR, ICESAT-2).

In addressing the objectives, our team provides guidance to the SWOT project about measurement requirements, product definition, geophysical error sources, algorithm development, calibration, validation, and continue acting as a liaison with the broader science and applications communities interested in these coastal regions. We are convinced that our international team of researchers from USA, France and Canada has the necessary expertise to advance SWOT applications in these complex coastal systems.

Laurence Smith/Brown University
Advancing Northern Hgh-Latitude Hydrological Science through SWOT Water Surface Elevation Mapping
19-SWOTST19-0057

The northern high latitudes contain the greatest abundance of terrestrial surface water bodies on Earth. They are important for ecosystems, the carbon cycle, and people, and are sentinels of climatic change. Remote sensing studies indicate that many Arctic lakes are disappearing, and that the region's numerous large anastomosing (multi-channel) rivers are prone to ongoing avulsions (channel captures) that reconfigure water flow across complex, low-relief floodplains and deltas. Lack of vertical water surface elevation (WSE) observations limits our understanding of both processes. SWOT's all-weather, dense orbital coverage toward the poles thus presents a unique opportunity to advance scientific understanding of the world's most extensive yet inaccessible surface-water systems.

The proposed research seeks to answer two exciting science questions about northern high latitude lakes and rivers through SWOT observations: 1) Is the spatial distribution of freshwater storages in Arctic lakes influenced by permafrost state? 2) What are the spatial and temporal dynamics of water fluxes through anastomosing river systems, and how do they impact passage of water and sediment through complex, ecologically important northern deltas and floodplains? The first question, addressed at the circum-Arctic scale, will determine if solid wintertime freezing of lakes protects freshwater lake storages in permafrost terrain. We hypothesize that conflicting remote sensing reports of lake trends in continuous permafrost is caused by presence of taliks (thaw bulbs) beneath some lakes but not others, due in part to formation of bedfast (solidly frozen) lake ice in winter. The second question, addressed at the local to regional scale, will determine if gradual, in-progress river avulsions can be remotely identified from space. We contend that SWOT observations of WSE, water surface slope (WSS), discharge (Q) and stream power portend a powerful new way to map gradients in energy and water flux critical to channel evolution and the success or failure of river avulsions.

Both science questions will be tackled through pre- and post-launch research activities. Pre-launch activities include mapping bedfast lake ice throughout the continuous permafrost zone using Sentinel-1 C-band radar. Because taliks do not develop beneath

bedfast ice, this will identify lakes that likely lose water storage to infiltration vs. those that do not, an idea that will then be tested using SWOT WSE measurements post-launch. Other pre-launch activities include refining the SWOT Rivers Database (SWORD, the mission's global a priori river map) for 25-30 northern floodplains and deltas such that long (>10 km) anastomosing river reaches are sampled by SWOT; and analyzing previously acquired AirSWOT imagery and field data from the Peace-Athabasca Delta, Canada, where a major avulsion may be underway. Hypothesis-driven post-launch activities include analyses of SWOT WSE observations over lakes; and WSE, WSS, Q, over rivers. Three field trips will collect in situ measurements needed to confirm or refute inferred areas of enhanced river erosion and avulsion potential from these observations.

The investigators have deep expertise in hydrological remote sensing and field work in northern environments. The PI has actively participated in SWOT's development since conception, and has proven track records of pursuing interesting science questions and inclusive recruiting of talented, diverse young scientists into the remote sensing hydrology community. This proposal is responsive to 3 (of 5) Core SWOT Hydrology Science Questions and to broader NASA priorities, including Core Context #3 ("Safeguarding and Improving Life on Earth") of Strategic Goal 1.1 ("Understand the Sun, Earth, Solar System, and Universe") of the NASA Strategic Plan 2018; and Recommended Observation Capability #4 ("Trends in water stored on land") of the 2017 Decadal Survey for Earth Observation from Space.

Kendall Smith/New York University
Inferring Ocean Transport from SWOT
19-SWOTST19-0060

Quantifying the distribution of vertical exchange between the ocean surface and interior is key to constraining global carbon and energy budgets. Yet, direct observations of fluxes are sparse, and connections to the flow structures setting the transport is challenging. Evidence suggests that fronts are vertical-flux-hotspots, though the statistics of their distribution, structure, and associated transport remain theoretically and observationally unconstrained. Global remote sensing at SWOT scales offers the potential to constrain the statistics of fronts, and hence to constrain biogeochemical fluxes across the global ocean. The latter, however, requires a theory or empirical model connecting frontal SSH to vertical transport.

The first phase of our SWOT ST project focused on quantifying vertical transport in submesoscale-permitting simulations, revealing, for example, the partition between mesoscale vs. submesoscale, and balanced vs. unbalanced transport of tracers (Uchida et al., 2017, 2019). In the next phase, our goal is to develop robust algorithms to estimate vertical fluxes from SWOT observations. This phase of the mission will see the first real data from the satellite, so our end goal is to produce derived products from actual data.

Persistent challenges lie in the way of these goals. First, SWOT will observe lateral scales where ageostrophic motions project strongly onto SSH, obviating geostrophy alone as a method by which to infer velocities. Second, the ageostrophic flow itself must be decomposed: internal waves do not contribute to vertical transport (Balwada et al. 2018), but (ageostrophic) frontogenesis may be a key player. Moreover, the low-temporal sampling rate of SWOT data means time-averaging cannot be used to remove the wave-component of the flow. Finally, even given an algorithm to extract the transport-active velocity from SSH, one still needs process models and theory to relate surface estimates of velocity fields to vertical flux rates.

Recently, during his PhD work with Abernathey, Sinha (2019) used simulated ocean data to train a deep neural net to estimate velocities from a small neighborhood of SSH and other observables. This model was able to re-learn the physics of geostrophy and Ekman balance. Here we propose to extend this approach to submesoscale-resolving data, where frontogenesis, internal waves and other ageostrophic effects imply messier physics.

An intermediate step will be training such an algorithm on data with submesoscale features, but free of waves. A common approach is to smooth output over a few days, but this smears away some submesoscale features, while also incompletely removing waves. Shakespeare & Hogg (2017) showed that temporal smoothing in the Lagrangian frame is more effective, as it removes the Doppler shift of wave frequencies by strong flows. Using experience gained in the analysis of particle trajectories in the LLC4320 simulation (Sinha et al. 2018), we will apply Lagrangian filtering to the LLC4320 runs. The result will be a global dataset of filtered simulated data (to be shared with the community), which will be used to train our method to extract (wave-free) submesoscale velocities from SSH. Then, we will attempt to use a deep neural net to extract the waves from unfiltered simulated SSH from SWOT-simulator-sampled LLC4320 runs (and possibly also NATL60 and HYCOM). The methods, trained on simulations, will be validated against surface drifter data, which provide a ground truth velocity measurement.

Given a successful method for extracting submesoscale flows, we can return to the problem of connecting surface flow statistics with vertical fluxes. Here we will continue using the controlled submesoscale simulations from phase 1 to explore, using machine learning techniques to attempt to learn the averaged vertical fluxes below the mixed layer, using filtered surface SSH statistics, and climatologies of subsurface tracer and buoyancy.

Douglas Vandemark/University of New Hampshire, Durham
Assessing the Impacts of Surface Waves on SWOT Measurements
19-SWOTST19-0053

This research investigates new approaches to account for within-swath variability of surface wind, sea state, and the Ka-band sea state range bias on SWOT range noise and bias at spatial scales of 5-120 km. While baseline SWOT data processing algorithms and data product definitions exist (Esteban-Fernandez et al., 2017) for radar backscatter, wind

speed, sea state bias (SSB), nadir-only significant wave height (SWH), and across swath SWOT range noise characterizations, this project will investigate model refinements across this related suite of measurements and corrections. We believe refinements are possible largely because of recent advances gained from new ocean radar satellites that include SARAL/AltiKa, the Global Precipitation Mission (GPM), Sentinel 1 and 3, and CFOSAT. The project approach will be to two-fold, first we will address issues related to cross-swath wind speed, SWH, and sea state bias using data and models derived from existing global wave model data combined with conventional altimeter and supporting synthetic aperture radar (SAR) and near-nadir radar satellite datasets at Ku- and Ka-band. As part of these studies, we will start from these questions: What can be detected and quantified across each swath? and What are the likely forcing factors and ancillary parameters that may help with SWOT range noise and bias mitigation? The second part of our approach will involve detailed assessment of wave impacts on SWOT ocean range measurement characteristics from near to far swath incidence angles using the high rate data available only during the 90-day fast phase mission period at crossovers; this in comparison to the low rate ocean range and range uncertainty data that will be provided for the rest of the mission. One goal is to quantify the benefits and limits obtained using this onboard processing approach. The work plan combines satellite observations and radar scattering models in a pragmatic approach - examining these issues using both pre- and post-launch studies. The project team brings expertise in Ka-band ocean radar measurements near nadir, altimeter sea state bias and wind speed algorithms and their physical basis, satellite remote sensing of ocean gravity waves using SAR and the new CFOSAT scanning wave spectrometer, and precision ocean radar range measurements. A salient addition will be combined use of new numerical sea surface simulations and cross-track CFOSAT satellite high resolution Ku-band radar data at 2-4 deg. incidence angles (similar to SWOT). This will provide a pre-launch SWOT pathfinder addressing certain aspects of near-nadir ocean imaging as well as potential benefits and insights for SWOT data assessments after launch.

Jida Wang/Kansas State University
Integrating Reservoirs into SWOT's Global Surface Water Storage and Discharge Monitoring
19-SWOTST19-0064

Water storage in lakes and discharge in rivers are two fundamental components of surface hydrology. Understanding their spatiotemporal dynamics is among SWOT's primary science goals. The current Science Team (ST) is treating water storage change and river discharge as two separate products. Since reservoirs are regulated water stores on river channels, they are crucial in bridging storage and discharge. In this project, we propose an integration of global reservoirs into an improved storage-discharge monitoring for SWOT, by completing four successive objectives.
The first two objectives relate to a priori data preparations, and will be achieved before the scheduled launch of SWOT. Obj. 1 is to establish an a priori global reservoir database. We will synergize our own research accumulation in dam/reservoir inventory with other available dam registries and water mapping, to compile a comprehensive a

priori global reservoir database for SWOT. This database will include not only fine-detailed spatial masks of a vast number of reservoirs, but also their attributes/metadata that are critical to sufficing SWOT's accuracy and consistency requirements for reservoir storage monitoring.

Obj. 2 aims to harmonize the a priori reservoir, lake, and river databases. The developed a priori reservoirs from Obj. 1 will be integrated to our UCLA Circa-2015 Lake Inventory, which will form a global waterbody dataset where reservoirs are distinguished from natural lakes. These waterbodies will then be carefully harmonized with existing a priori river databases. Through this harmonization, each hydrologic unit (i.e., lake, reservoir, and free-flowing river reach) will be geometrically isolated to ensure the accuracy of SWOT's storage change and discharge estimations, and meanwhile topologically connected to enable the understanding of storage-discharge interactions.

The remaining two objectives emphasize discharge algorithm improvements and scientific applications. Both will be achieved using the harmonized storage-river databases and SWOT's data collection after the launch. Obj. 3 is to improve the estimation of reservoir inflow and outflow, which is critical to water management and has not been adequately addressed by the existing discharge algorithms. This objective involves the development of a novel algorithm that accounts for the mass balance between water stores and surrounding reaches. This algorithm relies largely on SWOT measurements to parameterize the channel properties that cannot be observed by SWOT, for the reaches both immediately upstream and downstream of each reservoir. The parameterized channel properties, together with SWOT data collection, will then enable the estimation of reservoir inflow and outflow.

Obj. 4 aims to analyze reservoir impacts on seasonal storage-discharge interactions. We will apply our results from the previous objectives to address two scientific questions: "How do reservoirs alter the intra-annual flow regime in global rivers, and how does the impact vary in reservoir purpose, stream order, climate aridity, and geopolitical settings?" The study will have significant implications for reconciling water managements in climate-sensitive and international watersheds, and improving reservoir schemes for hydrologic models.

This proposed research is highly responsive to SWOT ST's research priorities for terrestrial hydrology. Its objectives to harmonize storage and river datasets and improve reservoir inflow/outflow estimates promote "development and implementation of algorithms to produce river discharge estimations" and "assimilation of SWOT river, lake, and/or wetland data" (A.12-5&6, ST Amend 2019). Its scientific investigation on reservoir seasonal impacts on storage-discharge interactions improves our answers to "what is the spatial distribution of freshwater storage and runoff through rivers, lakes, and reservoirs?" and "what are the impacts of water impoundments… on the global water cycle?" (A.12-5)