Title

Regional Ocean State Estimation for SWOT: Resolving Variability in the California Current System

Investigators

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General objectives and approach

SWOT will measure ocean sea surface height within parallel 50-km-wide swaths, providing measurements at 2 km spacing with an effective resolution of about 10 km, but with 21-day gaps in time between measurements and gaps in space of several hundred kilometers between swaths collected over 3 to 4-day time intervals. A major challenge for SWOT will come in deciding how to make best use of these observations. High-resolution assimilating ocean models offer one strategy for studying the 10-km-scale processes resolved by SWOT, while bridging the spatio-temporal gaps between satellite observations. In data assimilation, a numerical model is constrained by observations. Data assimilation provides a means to fill in gaps between sparse observations with an ocean circulation that is consistent with the physics that drives ocean circulation. Our group's ongoing contributions to the SWOT science team have been directed toward developing 4-dimensional variational (4dVar) assimilation at the space and time scales needed for SWOT, using the MIT general circulation model (MITgcm).

In this project, we aim to implement an assimilating ocean model for the region of the California Current, building on existing regional assimilation capabilities (Todd et al, 2011, 2012; Mazloff et al, 2014, Zaba et al, 2018). Our regional model will aim to replicate SWOT's spatial resolution and to resolve the small-scale features that SWOT is in principle capable of resolving. Figure 1 shows our model domain.

On length-scales larger than 50-100 km, ocean circulation is dominated by geostrophic motions, in which pressure gradients balance the Coriolis effect associated with the Earth's rotation. At smaller scales, SWOT's sea surface height measurements could reflect the additional influences of internal waves, baroclinic (depth-dependent and time-varying) tides, and surface waves. These small-scale processes have commonly been omitted from assimilating ocean models. A key goal for our research effort is to develop the capabilities to represent internal waves, baroclinic tides, and surface waves within an assimilating framework. This has involved developing new strategies for forcing tides, for including surface waves and wave--current interactions, and for representing internal waves.

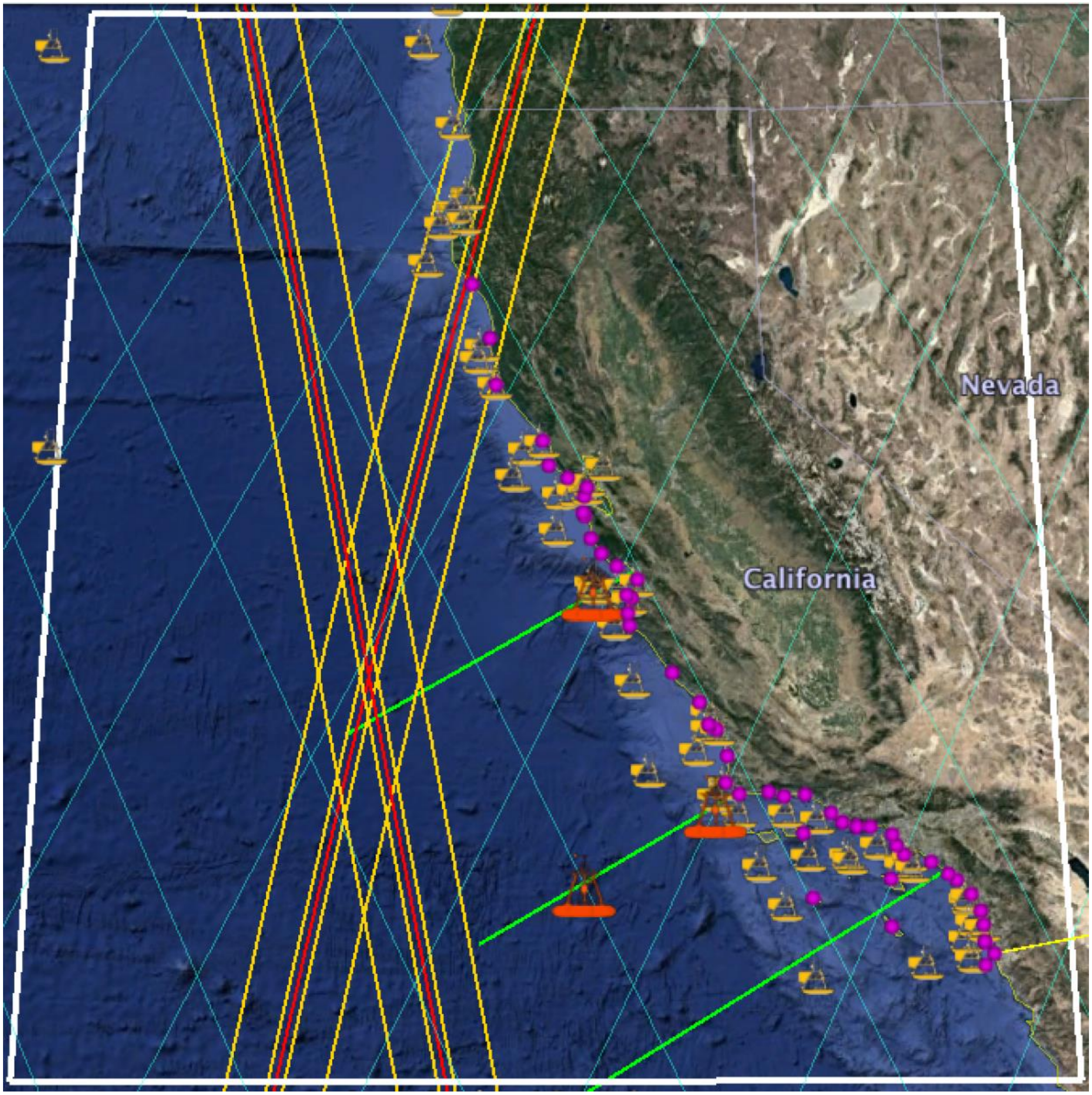

Figure 1. Model domain (130°W-16°W, 31°N-43°N; bounded by thick white lines) used for California Current regional modeling and assimilation experiments. Green lines indicate gliders, magenta dots are High-Frequency radar locations, National Data Buoy Center sites are yellow symbols, Southern California Coastal Ocean Observing System (SCCOOS) moorings are red, and nadir altimetry groundtracks from the TOPEX/Poseidon/Jason satellite series are cyan. The SWOT one-day repeat swaths are indicated in yellow, with nadir tracks shown in red. Blue shading indicates bathymetry.

Internal waves have proved to be a major challenge for this effort. The propagation of internal waves depends on the stratification of the ocean, and high vertical resolution is needed to sustain internal wave activity within a model. Internal waves are generated through a number of processes, including the effects of tides moving over rough topography, so researchers initially hypothesized that by including tidal forcing and high vertical resolution, we would readily be able to model realistic internal wave behavior. A surprising result of recent SWOT-supported analyses of observations and global model results from the California Current region is that much of the regional internal wave energy found in the California Current region originates thousands of kilometers away and travels long distances across the Pacific Ocean to reach our study domain (Mazloff et al, 2020). Figure 2 illustrates this for a mooring location near Monterey Bay: a global high-resolution model (blue line) is able to replicate the high-frequency energy spectrum observed from mooring data (magenta line), but two different high-resolution regional models (green lines) lack this high-frequency energy. At resolutions high enough to support internal waves, carrying out data assimilation for the global ocean, or even the entire Pacific Ocean, would have prohibitively expensive computational costs. Thus we aim to apply boundary conditions that will supply our regional model with sufficient internal wave energy to produce physically realistic small-scale internal wave behavior.

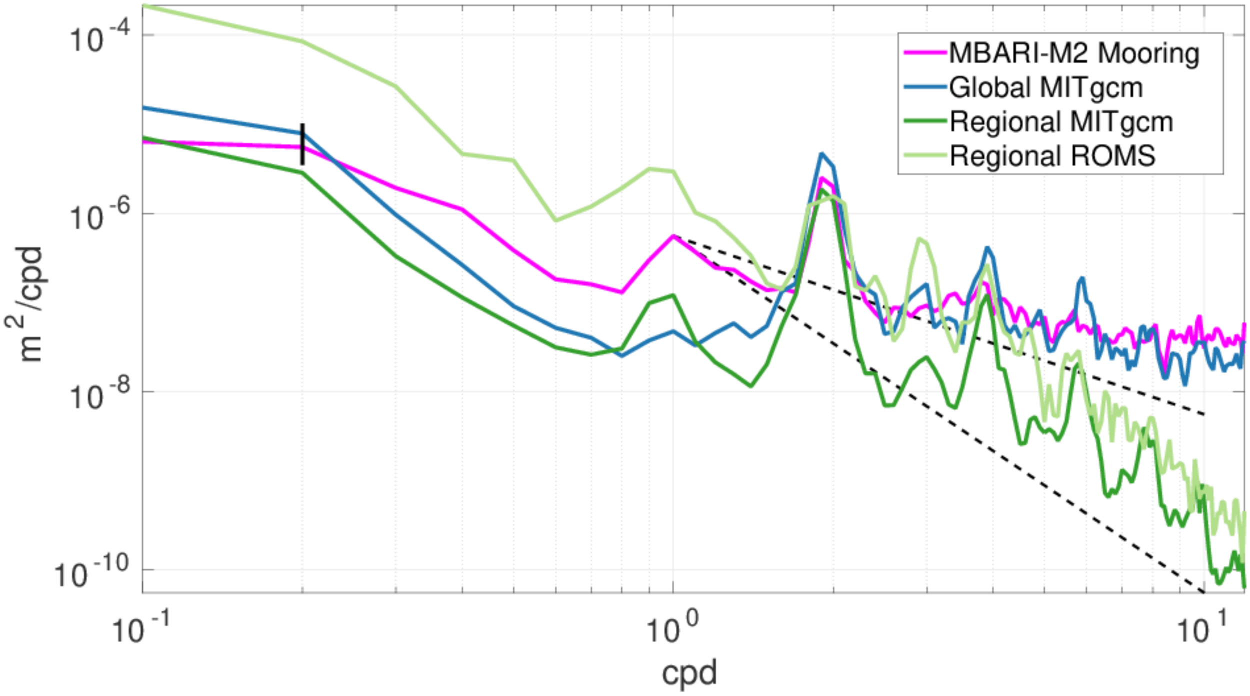

Figure 2. Power spectra density at the Monterey Bay Aquarium Research Institute (MBARI)-M2 mooring, computed using steric height in the upper 300 m from the mooring observations, a global 1/48° version of the MITgcm (llc4320), and regional models run at the same resolution. Mooring location is the northern red "buoy" symbol in Figure 1. The dashed lines denote slopes of -2 and -4. Adapted from Mazloff et al (2020).

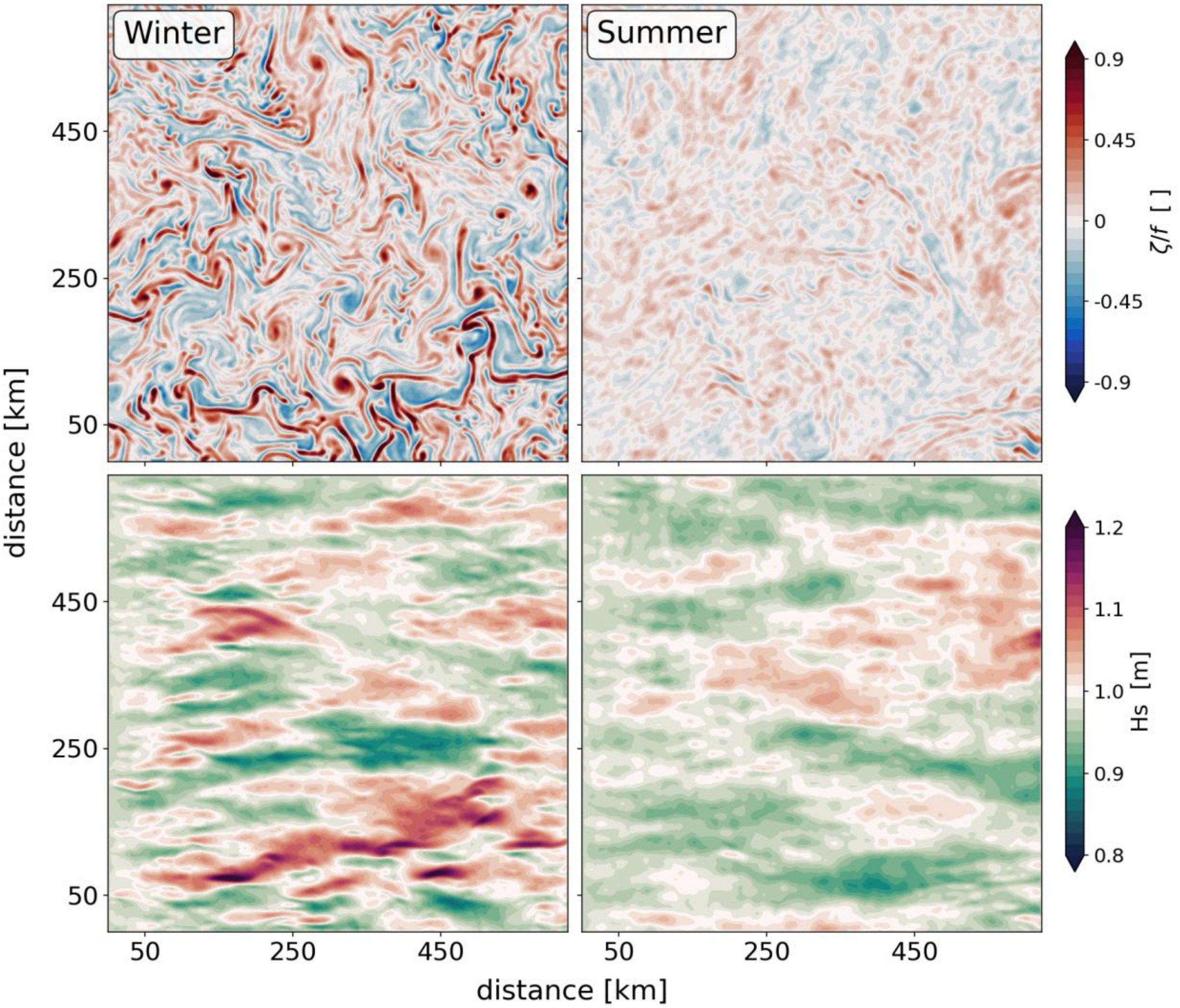

Figure 3. (Upper panels) Snapshots during winter (left) and summer (right) vorticity fields from the MITgcm llc4320 global simulation in the California Current region. (Lower panels) Corresponding significant wave height Hs for the same two seasons from an idealized wave model setup forced with the MITgcm currents. In this particular setup, Hs for a case without currents would be uniform and equal to 1 m in the entire domain. This figure shows that the marked contrast in Hs spatial variability can be attributed to the influence of the ocean current vorticity.

Although SWOT will not be capable of resolving surface gravity waves, this type of wave will be an important source of noise for SWOT's measurements. Recent simulations of wave-current interactions (Villas Bôas et al, 2019, Villas Bôas and Young, 2020) demonstrate that waves are modulated by ocean currents over the scales of eddies and fronts, which means that we can expect strong gradients in the sea state within SWOT's swath. Figure 3 shows that even with the comparatively weak currents of the California Current System, seasonal differences in the spatial scales of the background vorticity lead to corresponding differences in significant wave height (Hs). One of our goals is to estimate Hs using our coupled ocean-wave regional model configuration in order to place bounds on the uncertainties in SWOT's SSH retrievals. This will allow us to assign low uncertainties to SWOT sea surface height measurements when wave conditions are unlikely to lead to retrieval difficulties, while down-weighting SWOT data that could have biased sea surface height retrievals due to wave conditions.

Expected results

- This project will demonstrate ocean model assimilation capabilities for high-resolution processes that are relevant for SWOT and to identify the time and space scales and the physical processes that can be effectively represented through assimilation. This work will lay the foundation for future regional state estimates in other parts of the world and for high-resolution global state estimation.
- The 4dVar assimilation will provide a formal means to map the SWOT data at the time of satellite overpasses and to propagate signals in space and time between overpasses in order to fill the spatio-temporal gaps left by SWOT's sampling pattern. We will release an optimized dynamically consistent state estimate to use in exploring processes occurring within the California Current (SWOT cal/val) domain.
- The dynamical framework of the state estimation will allow us to distinguish geostrophic components of sea surface height from motions that are not strictly geostrophic (e.g. baroclinic tides, surface waves, internal waves). This will serve as a tool for analyses of the physical processes resolved by SWOT, including assessments of processes observed as part of cal/val. Using the state estimate, we will specifically assess the relative contributions to sea surface height of balanced motions, stationary and non-stationary tides, internal tides and waves, and surface gravity waves.

Milestones:

SWOT is now scheduled to launch in 2022. Just after launch, the satellite will spend 180 days in a one-day repeat orbit to support instrument assessment, calibration, and validation (cal/val). Subsequently it will move to a 21-day repeat. Our objectives can be divided into pre-launch, cal/val, and science-orbit activities.

Pre-launch

Prior to the SWOT launch, we are focused on testing strategies for incorporating surface wave effects into the state estimate and for managing open boundary conditions in regional internal-wave-resolving models and will test these by carrying out a state estimation trial using data collected in the SWOT pre-cal/val experiment as well as extended time series collected as part of the Southern California Coastal Ocean Observing System (SCCOOS), including high-frequency radar data (Kim et al 2010, 2011), Acoustic Doppler Current Profiler (Chereskin et al 2019) and glider observations (Todd et al 2011, 2012; Rudnick et al 2017; Zaba et al, 2016, 2018).

Cal/Val

During the one-day repeat, we will focus on making use of the initial SWOT data, both to assess the structure of sea surface height in the California Current region from the measurements and to use as a constraint for our regional state estimation. If data quality permits, our objective is to run a near-real-time assimilation over 5 to 30-day time periods in order to evaluate the 4dVar response to SWOT constraints.

SWOT science orbit

Once SWOT transitions to its baseline 21-day-repeat science orbit, our work will focus on state estimation over 21- to 30-day periods to bridge the gap between satellite revisits. The full dynamics of the MITgcm constrained via 4dVar to SWOT observations and other available remote sensing and in situ observations will provide a dynamically consistent model estimate of the circulation. We will progressively refine our state estimation products, evaluate the range of near-real-time or operational state estimation products that could be made available for SWOT, update releases of our software and data products, and finalize manuscripts discussing the findings that emerge from interpreting the SWOT state estimate alongside SWOT observations.

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