Project Summary

Barotropic and baroclinic tide models for and from SWOT

Richard Ray (NASA Goddard Space Flight Center), Gary Egbert (Oregon State University), Sam Kelly (University of Minnesota, Duluth), Edward Zaron (Oregon State University)

1. Introduction & Objectives

The SWOT wide-swath altimeter mission is an exciting and challenging mission for tides. SWOT promises to provide the community with a wealth of new high-resolution measurements that can be used to study both barotropic and baroclinic tides. In fact, SWOT's orbit was designed in part to be useful for studying tides. While barotropic tide prediction in the deep ocean (between the latitudes ±66°) is now approaching the 1-cm accuracy level (Ray & Egbert, 2017), SWOT will provide valuable new measurements in near-coastal waters and in the polar seas to latitude 77.6°, regions where models remain less accurate. But the real tidal focus of SWOT, in light of its primary objectives in submesoscale oceanography, will be baroclinic tides.

First-mode baroclinic tides have typical wavelengths in the deep ocean of order 100-170 km for semidiurnal tides, double that for diurnal tides. Higher modes have shorter scales. These tides thus fall directly into the prime mesoscale and submesoscale regime that SWOT is designed to study. It will be critical to remove as much of this tidal variability in SWOT data as possible. Our project aims to develop both barotropic and baroclinic tidal models to support this goal and to deliver models to the SWOT project teams that can be employed for the initial processing of SWOT data.

Once SWOT begins collecting data, now scheduled for early 2022, the mission itself will be a prime source of new knowledge of baroclinic tides, which will allow both improvement of existing models and better understand of tidal baroclinic waves and their variability. We are especially excited by potential discoveries arising from SWOT's initial 'cal/val' one-day repeat orbit. During those 90 days, we will observe seven full cycles of the (aliased) M2 tide, with an opportunity to study rapid temporal variability not possible during the primary mission.

2. Approach

2.1 Barotropic Tidal Models

The GOT and TPXO series of global tide models that our group has developed over the years have been extensively used by the satellite altimeter community and also, through many varied applications, by the wider geophysical community. Our efforts to support SWOT build on these existing global models. We intend to focus on model inadequacies in high latitudes and in near-coastal and shallow-water regions.

Over the past decade the satellite altimeter community has been extending altimetry into the near-coastal zone, with many efforts devoted to improving "coastal altimetry" (e.g., Vignudelli et al., 2011). The high spatial resolution of SWOT will considerably strengthen the field of coastal altimetry. But to support those efforts we need to improve our abilities to predict the near-coastal tide. SWOT data themselves will be a valuable new source of tide measurements in these regions, especially once several years of data have been collected. Our main approach to the problem of shallow-water and coastal tide prediction will rely heavily on the Oregon State Tide Inversion Software (OTIS) and its ability to run series of nested inverse models that attain required higher resolutions in shallow water.

Figure 1 is an example of the kind of inverse-model nesting that we are now employing to improve near-coastal tide models. Panel (a) shows one of our global models in the seas surrounding Australia. King Sound (the small box on left) is a medium-sized bay with fairly complex tides; it is a location where all of our standard global models perform poorly according to local tide-gauge measurements. Panel (b) shows a high-resolution (grid interval 0.5 km) local model which has been blended to the global model and which, while not perfect, agrees far better with local measurements. Inverse model TPXO.9 has taken this approach of employing a large suite of nested high-resolution models within the larger global domain, and we intend to develop these solutions further in preparation for SWOT.

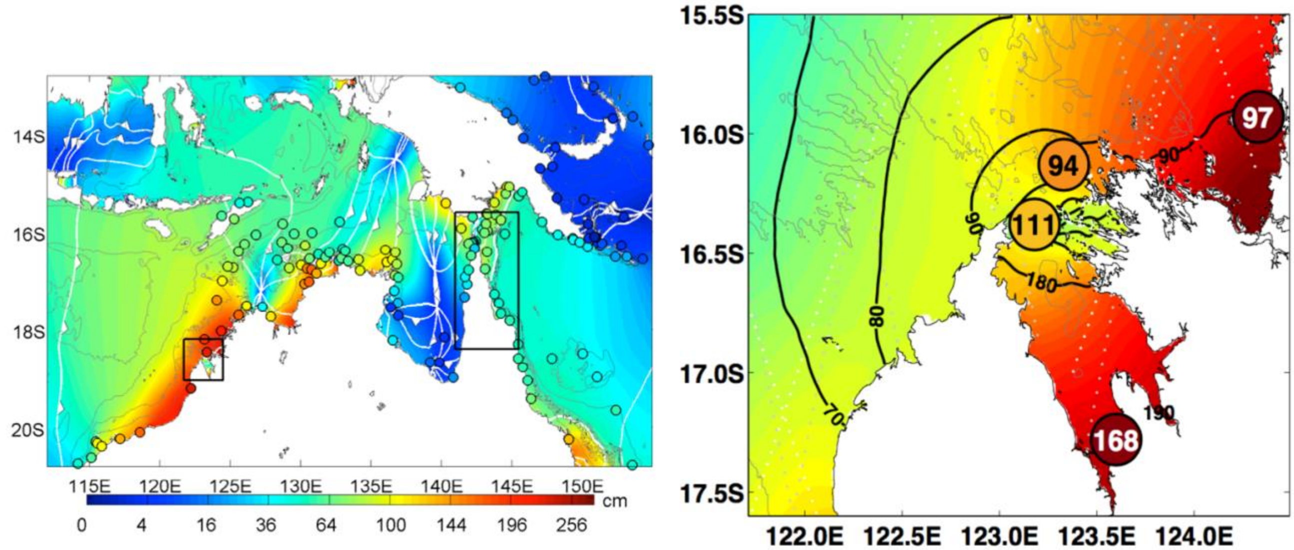

Figure 1. An example of nested high-resolution tide model, for King Sound on the northwest coast of Australia. Color circles denote tidal amplitudes determined from local tide gauges.

Work in polar regions is now benefiting especially from CryoSat-2 observations (e.g., Zaron, 2018). Unlike previous altimeter missions overflying the high latitudes, CryoSat is not sun-synchronous, so it is useful for studying solar tides. Data are continuing to be collected, and now new ICESat-2 data have become available as well, so high-latitude tide solutions will continue to improve over the next few years, even before SWOT launches.

2.2 Baroclinic Tidal Models (Coherent)

Over the past few years we have used historical altimeter data to develop models of coherent low-mode baroclinic tides in the deep ocean (Ray & Zaron, 2016; Zaron, 2019). The goal has been to develop pre-launch models that will attempt to remove from initial SWOT data a large fraction of the sea-surface height variability induced by baroclinic tides. That work will continue during this new project and will be extended to include some part (fraction still uncertain) of the temporally incoherent tides. In fact, determining the nature of the incoherent tide, its variance relative to the coherent tide, the causes of incoherence, and a number of related questions, are all research questions that must be addressed during the investigation—not only by our team, but by the entire altimeter community.

We have taken three complementary approaches to mapping stationary internal tides. These are (1) empirical mapping based on along-track tide estimates extracted from exact-repeat mission altimetry; (2) a somewhat similar mapping of along-track data but based on utilizing basis functions that satisfy some expected local hydrodynamic constraints (e.g., tidal wavelengths restricted to theoretical values based on local, generally climatological, stratification); and (3) assimilating along-track data into a hydrodynamic model, using the inverse machinery of OTIS but running in a reduced-gravity mode. Each approach has advantages and disadvantages, and exploring each is already proving to be a useful endeavor.

So far the most encouraging results have been obtained with approach (2); an example of the mapped tidal field is shown in Figure 2. Displayed are mode-1 M2 internal tides in the tropical Atlantic Ocean, shown as a snapshot of SSH elevations in-phase with the M2 astronomical potential at Greenwich. Examination of phases (not shown) reveals propagation from a large number of wave sources. These waves combine by constructive and destructive interference, giving rise to the complicated field depicted in Figure 2.

Historical altimeter data are only marginally adequate to map the internal tides depicted in Figure 2. Nonetheless, this work will form the initial "internal tide correction" for SWOT altimeter data. A team of current SWOT investigators, led by Loren Carrere, has performed preliminary testing of several baroclinic models. One example test (Figure 3) shows the reduction in variance of independent CryoSat-2 altimeter data obtained by applying our baroclinic model as a correction. Throughout much of the ocean, and especially in regions of known sources of large internal tides, there is positive reduction in variance. The regions where the correction is poor—in fact, adding to the Cryosat variance—are mostly confined to regions of western boundary currents or other regions of high mesoscale variability; in those regions our mapped tidal fields are degraded by the high "noise source" of mesoscale variability, and moreover, in those regions it is quite possible that there is no stationary internal tide to be mapped. In other words, the high mesoscale has possibly destroyed the coherent internal tide signal in our maps as well as in the real ocean.

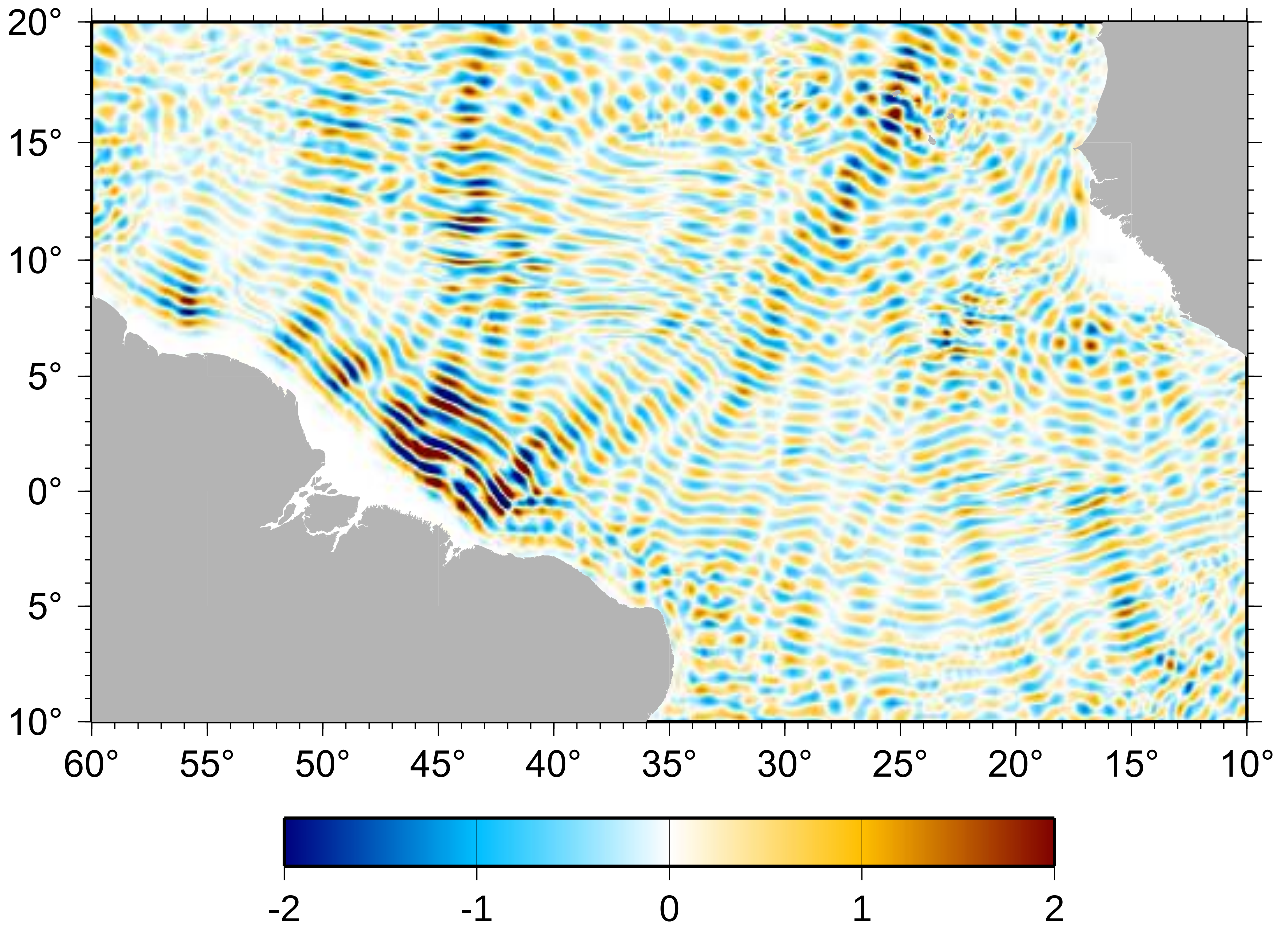

Figure 2. A snapshot of sea surface height (cm) of the M2 internal tide, from Zaron (2019). Some of the largest waves, such as those off the Amazon shelf, saturate the 2-cm color scale.

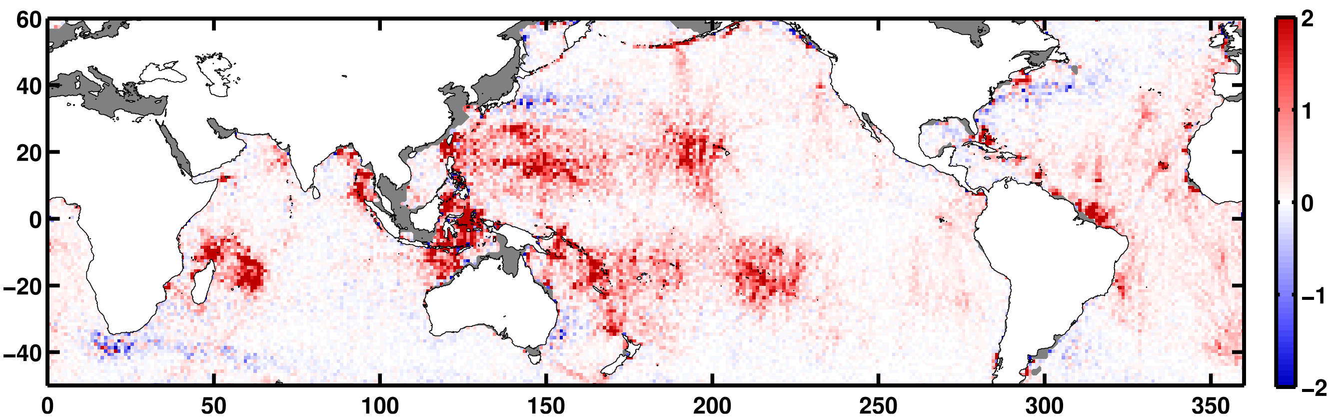

Figure 3. Variance reduction (cm^2) when applying one of our models as an internal tide "correction" to independent altimeter measurements from Cryosat-2. Red denotes positive variance reduction. Blue denotes degradation of the data, which occurs primarily in regions of high mesoscale variability.

2.3 Baroclinic Tide Models (Incoherent)

We have developed an approach to removing non-stationary internal tides which appears promising and merits further development. This development work will proceed as we approach the SWOT launch, and it will then be fine-tuned once real SWOT data are in hand.

The approach is based on using a principal components analysis of output from a high-resolution ocean simulation, such as HYCOM, to determine basis functions for subsequent tidal analysis. Tests using the SWOT Simulator are promising: variance reduction tests with CryoSat-2 data (used only for validation) demonstrate that the basic approach can work with real data. Figure 4 is an example where we have applied the method to the middle Atlantic Ocean; we already know from previous work based on altimeter wavenumber spectra that this is a region with predominantly incoherent internal tides, and indeed the figure shows such dominance.

In addition to developing principal components from HYCOM we also intend to examine other models. One of these will be the coupled-mode shallow water (CSW) model developed by Co-I Kelly, which can be run with time-variable background currents and stratification. Since the CSW model is comparatively cheap to run (and we can do this ourselves), use of this model provides us with the capability to explore more thoroughly various issues that arise in the principal-component approach.

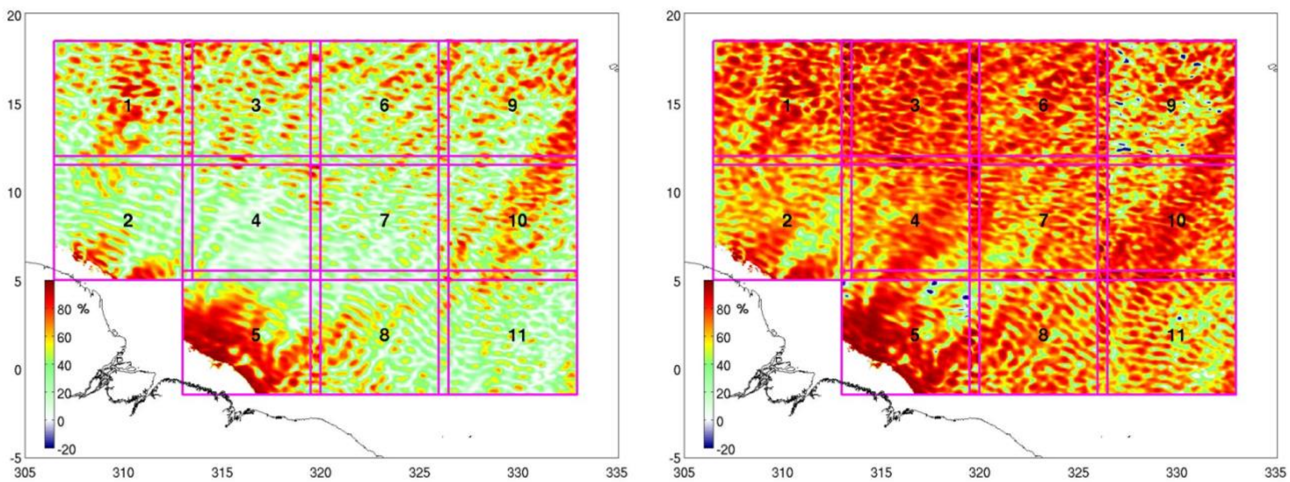

Figure 4. Percent variance of HYCOM internal tides explained by (left) stationary tides and (right) stationary + non-stationary tides, where the non-stationary are determined in part by a principal components analysis of HYCOM. This technique represents a promising approach to removing both coherent and incoherent internal tide signals from SWOT.

3. Anticipated Results

In the near future we expect to deliver to the SWOT project teams a set of models that can be used in processing of early SWOT data. Based on results such as shown in Figure 3, we have some confidence that these models will be capable of removing undesired tidal variability from the SWOT data. We also anticipate that these models will be far from perfect, and they will undoubtedly be deficient in removing non-stationary tidal energy. Efforts to address that problem, as we analyze the new SWOT data—both the cal/val data during the first 90 days as well as the primary mission data—will be our primary focus in the later years of this project.

References

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