Research and Development of SWOT Measurements in the Canadian Oceans

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1. Introduction and Objectives

From the Atlantic, the Arctic to the Pacific Oceans, Canada has the longest coastline in the world. The vast coastal zone and continental shelves feature harsh environmental conditions, complicated physical processes, diverse ecosystems and rich hydrocarbon resources. It is difficult and costly to install and maintain field instruments in so vast regions. At present, there are only very limited long-term tide-gauge stations for sea level observations and almost no long-term current measurements. As a result, many physical processes including tides, coastal jets, and mesoscale and submesoscale features are not well observed or understood.

Nadir satellite altimetry has allowed for the observation of ocean tides and general ocean circulation from space (Fu and Cazenave, 2001). The poor accuracy in the coastal, shelf and polar oceans are in large part due to inadequate spatial resolutions and complicated non-linear hydrodynamics. There are notable discrepancies of the barotropic tide correction models along the tracks across the Canadian coastal oceans. These discrepancies represent the uncertainty in the barotropic tide models. Models of baroclinic tides, or internal tides, face very similar challenges. Interactions with geostrophic currents create incoherent internal tides (i.e. internal tides not synchronous with the barotropic tide) (Nash et al., 2012; Shriver et al., 2014). In turn, incoherent internal tides are currently virtually impossible to remove from raw signals, making the diagnosis of geostrophic currents difficult. Near-inertial waves, namely internal waves generated by the wind, pose a rather different challenge: invisible to altimetry (Klein et al., 2009). Near-inertial waves stimulate dissipation of geostrophic flows.

Multi-mission satellite altimeter data are widely used for studying ocean circulation variability and for constraining circulation models in the deep ocean. Assimilation of these data into circulation models has significantly improved ocean state estimation and prediction. However, in shallow waters from the coast to the continental shelf edge, there have been relatively few applications of altimetry to analysis of currents and submesoscale variability. The limited use of altimetry results in part from the large uncertainty in correcting for the oceanic tides (e.g. Han et al., 1993) and from coarse spatial resolutions. Sea level variability in coastal regions usually has shorter space and time scales than in the deep ocean. Even with a combination of multiple altimeters it is often difficult to achieve adequate spatial and temporal sampling. Furthermore, variability is strongly anisotropic on the shelf due to significant influences of bottom bathymetry, which poses challenges to statistically based methods such as optimal interpolation used to produce spatial sea level anomaly maps from along-track data (Ducet et al., 2000; Cherniawsky et al., 2004).

Until now altimeter data were used in verification studies of ocean wave models, by making comparisons with satellite along-track measurements that collocate with model estimates for winds and waves, along the track of the satellite. Because of the narrowness of the swaths, only a simple scalar comparison scatter plot is possible.

The SWOT (Surface Water and Ocean Topography) mission with its high spatial resolution of sampling, on the other hand, will provide unprecedented potential for observing and modeling coastal tides, currents and eddies (Fu and Ubelmann, 2014). The new capacity is particularly important for Canada's vast coastal zones and high-latitude seas, where conventional oceanographic monitoring is extremely challenging and costly. It is anticipated that we will face challenges in separating low-frequency features from high-frequency ones in SWOT data and in assimilating SWOT data into ocean circulation models.

The scientific objectives for this proposal are (1) to improve knowledge of coastal currents, mesoscale and submesoscale features, tides, marine winds and waves from existing nadir altimetry data, RADARSAT images, in situ measurements and numerical models in Canadian marine waters, and (2) to improve models for tide, circulation, internal tide and wave, and surface wave and to develop techniques that can effectively integrate simulated SWOT data into these models.

2. The Approach and Work Plan

2.1 Analysis of existing nadir altimeter and synthetic aperture radar (SAR) data

We will extend and enhance existing research on multiple mission satellite altimeter data from TOPEX/Poseidon, Jason-1, Jason-2, ERS, Geosat-Follow-On, Envisat, Altika and Cryosat-2. Along-track altimeter sea level data will be used to derive empirical tidal solutions (e.g. Cherniawsky et al., 2004), study storm surges (Han et al., 2012) and detect fronts, which will be evaluated against and integrated with field data. Along-track and mapped altimeter sea level data will be used to study shelf-edge currents and mesoscale eddy features and compared with in-situ observations from various DFO and international field programs. Altimeter data will also be used to extract marine winds and waves and evaluated against buoy data. We will examine Cryosat-2 and RADARSAT-2 data for oceanographic features in coastal waters and western boundary current regions and for evaluating SAR- and interferometer-based altimetry technique.

2.2 Improvement of coastal tidal and circulation models

We will improve high-resolution three-dimensional tidal and shelf circulation models for selected regions in the Canadian Atlantic, Pacific, and Arctic based on existing modeling work. These circulation models will resolve submesoscale features such as coastal upwelling and shelf-edge fronts that meet the requirement to fulfill SWOT objectives. We will generate simulated SWOT data in Canadian waters based on existing regional model output and a SWOT simulator provided by the Jet Propulsion Laboratory (JPL). Various error sources from orbit, instrument, and geophysical corrections will be considered in generating the simulated SWOT data. Empirical methods such as the Empirical Orthogonal Function (EOF) analysis will be used to extract mesoscale and mesoscale features.

We will use the Finite Volume Community Ocean Model (FVCOM), an unstructured grid, finite-volume ocean model (Chen *et al*., 2003; 2006), to simulate coastal tides and shelf circulation. The finite volume method integrates the momentum and tracers through individual unit control volume and solved numerically by flux through the volume boundaries to guarantee the conservation of mass and momentum. FVCOM has varying capabilities of data assimilation methods (nudging, optimal interpolation and Kalman filters). We will develop and improve 3-D barotropic tide models for selected areas off the Atlantic, Arctic and Pacific coasts, respectively. The model will include equilibrium and load tides. The effect of the water-column stratification on the mixing will also be considered through the turbulence scheme. A baroclinic circulation model for the Atlantic coast will be forced by wind, and heat flux at the sea surface. Synthetic SWOT and along-track data will be generated from the model solutions. Then the synthetic data with different resolutions and varying signal to noise ratio will be assimilated into the models.

2.3 Wave-current interactions and ocean surface features

In numerical studies, ultra high-resolution two-way dynamically coupled models for wave-current interactions in frontal regions of the Gulf Stream show evidence for the impact of strong submesoscale currents on ocean surface features, particularly ocean surface waves and sea surface heights. We will also improve coupled wave-current models for wave-current interaction features and a spectral wave model for infragravity waves. Our simulation will investigate the coastal area off Nova Scotia, including the Gulf Stream and related parts of the Northwest Atlantic, driven by atmospheric fields (such as winds) provided by simulations from WRF atmospheric model in addition to high-quality reanalysis fields such as the NOAA/NCEP CFSR V2 products. Synthetic SWOT data will be used in the simulations.

In the context of future wide-swath SWOT altimetry mission, oceanic infragravity waves need to be better quantified as they have wavelengths that will be resolved by such measurements. Moreover, the energies of these infragravity waves are expected to be a significant contribution to the error budget for possible measurements of the sea level height associated with submesoscale currents, at horizontal scales of around 1~10 km. Therefore, global numerical models of infragravity waves will likely be very necessary for the analysis of the planned SWOT mission. Preliminary versions of these models are presently emerging in the literature (Ardhuin et al., 2014). Thus, it will be possible to determine the noise level induced by the infragravity waves in the SWOT data, which will help to get the more accurate estimates of submesoscale currents in the open ocean and in coastal Canadian waters.

2.4 Interactions between internal tides and geostrophic flows

Few descriptions of the physical processes leading to internal tide decoherence currently exist, other than the fact that interactions with geostrophic flows are vital (Nash et al., 2012; Shriver et al., 2014; Ponte and Klein, 2015). In collaboration with Aurélien Ponte, we will undertake a fundamental study of the interactions between internal tides and turbulent nearly geostrophic flows. Parameter regimes to be investigated will consist of the geostrophic flow regime (mesoscale vs. submesoscale) and geographic regimes (continental shelf, tropical and detached western boundary currents).

In all studies, the leading thread will be to design de-tiding procedures for SWOT. De-tiding the signal will require a clear understanding of the dynamics at play, which is a focus of our research plan. Based on the knowledge acquired from our studies, and inspired by studies such as those of Callies & Ferrari (2013) and Bühler et al. (2014), we will seek a way to isolate internal tidal signals in simulated SWOT data, and to produce a freely-available algorithmic tool to do so in SWOT snapshots.

2.5 **Interactions between near-inertial waves and submesoscale geostrophic flows**

The dynamics of wind-generated internal waves (near-inertial waves) interacting with submesoscale flows such as fronts will also be studied. In collaboration with L. Thomas (Stanford), we will build on the experience gained previously and continue to study processes through which internal waves extract and dissipate geostrophic energy from fronts. The unsteady interactions between waves and frontogenetic configurations will be modeled numerically with flow_solve (Winters et al., 2004). Internal waves will be generated either at the surface by high-frequency wind stress, or by body forces in the volume of the fluid. The frontogenetic background flow will be varied in order to compare numerical results with the theory of Thomas (2012), and investigate the importance of the shape of the frontal region. We will also "zoom into" the core of the frontal region and perform high-resolution modeling of internal wave breaking, to study the small-scale physics of how waves break in fronts, and their impact on the energy budget of the latter.

We will study internal wave-mean flow interactions in light of the wave-mean flow theory. We will start from very basic configurations (one wave packet, one vortex or one front) with shallow-water numerical models and flow_solve and gradually increase the complexity of the simulations until they encompass a range of scales from the mesoscale flow down to the small-scale internal waves, similar to the semi-idealized ROMS simulations that we plan to use in the tidal decoherence problem. The goal is to develop a parameterization, which would reproduce the effect of the internal waves' action on submesoscale geostrophic flows, without having to explicitly resolve the internal waves. Particular attention will be devoted to detecting the surface signature of the internal waves' activity, in order to prepare for the arrival of SWOT data.

3. Anticipated Results

The proposal work addresses the first three oceanographic priorities for the SWOT Science Team, i.e. 2.2.1 Mesoscale and Submesoscale Processes; 2.2.2 Tides and High-frequency Motions; and 2.2.3 Interaction of Ocean Circulation with Mesoscale/Submesoscale. It also addresses the first secondary research priority, i.e., Coastal and Estuarine Processes.

The anticipated results are: (1) improved knowledge of coastal currents, mesoscale and submesoscale features, tides, marine winds and waves in Canadian marine waters; (2) improved models for tide, circulation, internal tide and wave, and surface wave; and (3) techniques that can improve the correction for oceanic tides, that can separate internal waves from geostrophic flows, and that can effectively integrate simulated SWOT data into these models.

The project results will improve regional tidal models for detiding SWOT data and improve regional ocean circulation and wave models that can effectively assimilate SWOT data, enhancing Canada's capacity in monitoring and forecasting ocean environments. The techniques for integrating SWOT data into ocean models and for separating low-frequency features from high-frequency ones will enhance the utility of SWOT data.

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