Integration of SWOT Measurements in Canadian Oceanographic Research and Operation

Guoqi Han (Fisheries and Oceans Canada), Will Perrie (Fisheries and Oceans Canada), Charles Hannah (Fisheries and Oceans Canada), Laura Bianucci (Fisheries and Oceans Canada), Nicolas Grisouard (University of Toronto), David Straub (McGill University), Jody Klymak (University of Victoria), Greg Smith (Environment and Climate Change Canada), Pascal Matte (Environment and Climate Change Canada)

1. Objectives

1.1 Review of the Research Topics

The Surface Water and Ocean Topography (SWOT) mission can provide spatial sampling adequate to resolve important submesoscale features and coastal processes (Fu, 2003; Fu and Ubelmann, 2014) with unprecedented accuracy. The assimilation of SWOT sea surface slope data into a regional ocean model introduces dynamic and kinematic constraints into the analyzed sea level and surface circulation (Gaultier et al., 2016). The full analysis fields can be validated against various in situ data sets available from the Canadian coastal observational programs, such as the Atlantic Zone Monitoring Program (Therriault et al., 1998). Collocations with polarimetric imagery from RADARSAT-2 SAR potentially allow verification of SWOT-detected processes, particularly those related to retrievals of sea surface temperature fronts, mesoscale eddies, waves, and marine winds.

Prior to the launch of SWOT, the Canadian Space Agency (CSA) has launched a series of ocean satellite missions focused on synthetic aperture radar (SAR): RADARSAT-1 in 1995, RADARSAT-2 in 2007, and RADARSAT Constellation Mission (RCM), which consists of three new SAR satellites, launched in spring 2019. Until RCM, the RADARSAT-1/2 missions were not able to provide routine estimates of surface currents. RCM will offer daily coverage of the global ocean and up to four times coverage of the coastal oceans surrounding Canada, particularly polar regions. The rapid RCM revisit frequency introduces a range of applications that are possible through the creation of composite images that highlight changes with time. These applications are particularly useful for monitoring the evolution of eddies, their interactions with ocean circulation processes, possibly including energy cascades to smaller scales. In addition, RCM will have a Doppler processor, which opens a door to retrieval models and thus, high-resolution observations of ocean surface currents. The Doppler information can provide total radial surface velocity (Ekman current & wind friction drift, Stokes drift, geostrophic current, tidal etc.), which is different from geostrophic or quasi-geostrophic currents obtained from SWOT's SSH data, because it includes contributions from all surface motions. The latter will probably include the velocity of sub-mesoscale processes, which as mentioned above, do not obey quasi-geostrophic theory (Capet et al., 2008; McWilliams et al. 2016).

1.1.1 Coastal Oceanography and Mesoscale/Submesoscale Features

Gridded multi-mission satellite altimetry data were used to study interannual and decadal sea level variations (Han et al., 2016) in the Northwest Atlantic. Jason-1 and Jason-2 data were combined with tide-gauge data to study storm surges in the Gulf of Mexico, and the results were discussed in relation to SWOT (Han et al., 2017). Multi-mission along track altimetry data were used to derive the Labrador Current transport index (Colbourne et al., 2017). High-resolution along track altimetry was used to study the tidal front over Georges Bank (Dong et al., 2018). Cryosat-2 data were examined to show their potential for extracting coastal oceanographic features and mountain glacier change (Gower et al., 2017) in Western Canada. Challenges and prospects of coastal altimetry in observing sea level, storm surges and currents have been reviewed (Han, 2017) to help guide future applications.

Radar imagery has been analyzed to show ability to derive submesoscale features (Liu et al., 2016), ocean waves (Chen et al., 2016), sea ice (Li et al., 2016), waves and marine winds (Zhang et al., 2015), as well as surfactants and crude oil on the sea surface (Li et al., 2017a). Simulated RCM SAR data have been used for waves, sea ice, winds, oil (Li et al., 2017b; Zhang et al. 2018). Zhang and Perrie (2018) proposed a new approach to detect ocean surface currents from RADARSAT-2 backscatter measurements, which was applied to C-band RADARSAT-2 ScanSAR images during Typhoon Lan 2017 in the open ocean.

1.1.2 Ocean State Estimation

High-resolution coastal models were established and refined off Eastern Canada (Ma et al., 2017). The models are able to resolve small mesoscale features coastal fronts and small eddies. Simulated SWOT data have been generated from the model sea surface height and used to reconstruct sea surface height field and coastal currents using optimal interpolation (Ma and Han, 2019). Progress has been made in assimilating simulated SWOT data into a coastal ocean model (Han and Ma, 2019).

High-frequency nadir altimeter data are routinely assimilated into operational global, regional and coastal ocean models by Environment and Climate Change Canada (ECCC; Smith et al., 2015; Dupont et al., 2015; Zhai et al., 2017; Paquin et al., 2019) as part of the Canadian Operational Network of Coupled Environmental Prediction Systems (CONCEPTS) in collaboration with Mercator Ocean International. The assimilation of altimeter observations in these systems is essential to constrain the forecasted currents used operationally, e.g., for search and rescue, emergency response and marine navigation. The skill of forecasted currents has been shown to depend sensitively on the along-track resolution of altimetry data, in particular in kilometer-scale coastal prediction systems, highlighting the potential for improvements from SWOT.

We have contributed state-of-the-art dynamics for coupling between waves and ocean to COAWST physics (Liu et al., 2019a; 2019b). This allows investigation of upper ocean dynamics, including surface wave effects, Coriolis-Stokes force and Langmuir turbulence on subsurface currents, cyclonic and anticyclonic eddies, the kinetic energy spectrum and energy cascade. A spectral wave model for infragravity waves has been completed (Liu et al., 2019, submitted).

1.1.3 Interactions between unbalanced and geostrophic flows

Low-mode internal tides propagating in the deep ocean are largely insensitive to the geostrophic circulation and as a consequence, they are well described as coherent signals, i.e. phase-locked on the barotropic tide (Dushaw et al., 2011; Zaron, 2015). However, interactions between internal tides and geostrophic flows can be significant. Far from topography, observations (Carrère et al., 2004; Rainville and Pinkel, 2006; Chavanne et al., 2010) and numerical models (Zaron and Egbert, 2014; Ponte and Klein, 2015; Dunphy et al., 2017) have shown that the mesoscale geostrophic circulation refracts internal tides. They have also shown that these interactions are strong in the shelf and coastal ocean (Nash et al., 2012), and near the equator and in western boundary currents, creating highly incoherent internal tides. These locations are also where submesoscale flows are strong. There is mounting evidence that unbalanced motions in general will dominate the SSH signal, depending on the location and time of year (Callies and Ferrari, 2013; Rocha et al., 2016; Qiu et al., 2018; Torres et al., 2018). Concurrently, as the scales decrease, coupling between balanced and unbalanced motions increases. A few theoretical studies have begun to scratch the surface of the fundamental processes at play (Young & Ben Jelloul, 1997; Dunphy & Lamb, 2014; Taylor & Straub, 2015; Grisouard and Thomas, 2015, 2016; Wagner et al., 2017; Savva and Vanneste, 2018), but remain limited in the regimes that they explore. More recently, Torres et al. (2019) have obtained some success in retrieving the unbalanced signal, directly from SSH snapshots, using spectral properties of balanced and unbalanced motions. These results identify imbalance with inertia-gravity waves of a fixed vertical structure and apply to summer time midlatitude environments.

1.1.4 In situ observations of balanced and unbalanced motions

In-situ characterization of submesoscale balanced and unbalanced motions is notoriously difficult, even more so than in the numerical and theoretical studies mentioned earlier. This is largely because the scales of interest span a broad range, and shiptime is at a premium. One measurement approach is to use a ship's ADCP (Acoustic Doppler Current Profiler) to observe along and across-track velocities, and a Moving Vessel Profiler to map temperature and salinity while the ship is underway. At typical cruising speeds, both approaches yield data at roughly 1-km horizontal resolution. Similar methodologies were reported in previous work (Klymak et al., 2015), are envisioned for planned missions to calibrate SWOT with in-situ sampling in Southern California (Farrar et al.), and are similar to ongoing work by Chereskin and Gille (Scripps Institution of Oceanography). The ADCP records can be decomposed into balanced and unbalanced motions using the Helmholtz decomposition, and subsequently into internal wave and non-internal wave motions with the addition of the CTD (Conductivity Temperature Depth probe) data (Bühler et al., 2014; Callies et al., 2015). Surface quasi-geostrophy (SQG) has been shown to be a good model for lateral variance in strong ocean currents (Callies et al., 2015; Rocha et al., 2016), but in regions with weaker mean currents, lateral variance is better described by frontogenesis (Callies et al., 2015; Ferrari and Rudnick, 2000; Klymak et al., 2015). The northeast Pacific has a curious depth-structure, with the spectra that most closely match the frontogenesis hypothesis found at mid-depth in the summer, indicating either a mid-depth source of vorticity (potentially the coastline to the east), or a memory of the last winter in the lateral variability (Klymak et al., 2015).

1.1.5 Projections of balance and imbalance on to SSH and influences from surface layer dynamics

In the absence of tides, the total flow is often thought of as a superposition of the geostrophic circulation and eddy field (balance) and inertia-gravity waves (imbalance). As alluded to earlier, geostrophy typically dominates at large scales and imbalance dominates at scales below the mesoscale-submesoscale transition. The extent to which imbalance should be thought of as quasi-linear waves, however, is unclear and no doubt regime-dependent. On one hand, the waves may be sufficiently nonlinear such that relationships between SSH and surface velocities implied by the dispersion relation need not apply. On the other, high frequency (ostensibly) geostrophic modes can also contribute to imbalance. These can be excited, for example, by near-inertial advection of balanced potential vorticity. To further complicate the picture, surface ocean flows also include an Ekman-like component. This is strongly modified by surface currents (Wenegrat and Thomas, 2017) and, because pressure does not enter into the nonlinear Ekman equations, this flow is intertwined with near-inertial motions (which are also essentially pressureless). A further complication is that surface gravity waves modulate the air-sea momentum transfer, are refracted by ocean currents, and thus can impact both balanced and unbalanced motions near the mesoscale-submesoscale transition.

1.2 Scientific Objectives

The scientific objectives are (1) To improve accuracy of ocean circulation predictions by developing techniques that blend SWOT data with model dynamics and to improve knowledge on coastal oceanographic processes; (2) To understand the dynamics and kinematic processes of sub-mesoscale and mesoscale processes, including eddies, currents, ocean waves, etc., their role in ocean transport and circulation, and their feedbacks to the atmosphere; and (3) to better understand, characterise, and diagnose, theoretically and observationally, how near-surface flows near the meso/submesoscale transition project on to SSH.

2. Approach

2.1 Mesoscale/submesoscale features and coastal ocean processes

We will extend and enhance existing DFO and ECCC research on multi-mission satellite altimeter data from TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, ERS, Geosat-Follow-On, Envisat, Altika, Cryosat-2, and Sentinel 3. Especially, emerging coastal altimetry products will be explored for the Canadian coastal oceans.

The output from existing ocean models for the Canadian oceans and from the models developed in this proposal will be used to generate simulated SWOT data. Using the simulated data, we will study how to effectively and accurately retrieve coastal oceanographic features from SWOT data, such as coastal storm surges and fronts.

We will assess tidal information from regional ocean models in the Canadian coastal oceans against tide-gauge data. The assessment will also be carried out in reference to global tide models commonly used for correcting ocean tides in satellite altimetry data (e.g. the Finite Element Solution 2014 (FES2014) (Carrere et al., 2016) or later versions as they become available). These global tide models will likely be default ones for the ocean tide correction of SWOT data.

As a SWOT pilot project, we propose to collect SAR imagery from both RCM and RADARSAT-2, the latter with high resolution quad -pol imagery, to measure fine-scale ocean surface currents. Additional wind and wave data, collocating with any available SWOT or other pilot field experiments, will be provided by CFOSAT, the China-France Oceanography SATellite. We also propose to do high resolution (~100m) numerical model simulations for the Northwest Atlantic/Gulf Stream area (following Liu et al. 2016). This is using a wave-ocean current model system, COAWST, originated by Warner et al. (2010), which couples ROMS ocean model to ocean waves and simulates the upper ocean dynamics at high resolution.

Application of the high-resolution Regional Ocean Modeling System (ROMS), within COAWST provides numerical ocean model outputs which can be used as input to the SWOT simulator. Outputs from the SWOT simulator, with surface velocity observations from RCM, combined with other altimeter observations, like AVISO, and surface drifter data from the Drifter Data Assembly Center of National Oceanic and Atmospheric Administration (ftp://ftp.aoml.noaa.gov/phod/pub/buoydata) will allow the study of sub-mesoscale ageostrophic motions as well as oceanic mesoscale eddies.

2.2 Improvement of coastal circulation modelling using SWOT data

We will improve high-resolution three-dimensional coastal and shelf circulation models and prediction systems for selected regions in the Canadian Atlantic, Pacific, and Arctic based on existing SWOT and other DFO and ECCC modeling work. These circulation models will resolve submesoscale features such as coastal upwelling and fronts that meet the requirements to fulfill SWOT objectives.

2.2.1 A data assimilative coastal circulation model off Newfoundland

A coastal circulation model off Newfoundland based on the Finite-Volume Community Ocean Model (FVCOM) (Chen et al., 2003; Chen et al., 2006) will be used to conduct data assimilation experiments. FVCOM has been successfully applied in coastal regions such as the Newfoundland Shelf and adjacent embayments (Han et al., 2011; Ma et al., 2015), by using its advanced finite-volume scheme and adaptive triangular grids. The high-resolution FVCOM output utilized in this study has uniform 2 km unstructured grids in the horizontal. The model uses Newfoundland shelf simulation output (similar configuration to that of Ma et al. (2015)) as its initial condition and is forced by the hourly surface wind stress, shortwave and longwave flux, air temperature, humidity and air pressure data of the NCEP Climate Forecast System Reanalysis (CFSR) product. The tidal components are interpolated from the OSU TOPEX/Poseidon Global Inverse Solution (http://volkov.oce.orst.edu/tides/TPXO7.2.html).

The validated model results will be treated as “truth”. We will generate simulated SWOT data in Canadian waters using the 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. The synthetic SWOT data with different resolutions and varying signal to noise ratios will be assimilated into the models. Deterministic Ensemble Kalman Filters (DEnKF) will be used for data assimilation. The complexity of assimilative schemes and effectiveness of assimilation will be examined.

2.2.2 Coastal circulation models off the British Columbia

We propose to test the limits of SWOT data as a source of observations for the evaluation of coastal models. To achieve this, we will develop numerical models for two regions of the coastal zone of British Columbia: Queen Charlotte Strait (QCS) and Discovery Islands (DI). These two regions provide different geomorphological features, which will allow for the testing of SWOT data in different seascapes. For instance, QCS is a relatively wide strait (width up to ~25 km) with many inlets and narrow channels nearby (e.g. Broughton Archipelago, Knight Inlet, Seymour Inlet); meanwhile, DI is a complex array of narrow and deep inlets and channels that connect the Strait of Georgia and Johnstone Strait. Both regions are modelled with the Finite Volume Community Ocean Model (FVCOM), which uses unstructured grids that allow for varying resolution (the horizontal resolution of these two domains goes from ~50 m to 2-3 km).

The DI model extends from Johnstone Strait to the northern Strait of Georgia. It has >35,000 nodes and its horizontal grid resolution varies from ~90 m in Seymour Narrows to ~1.7 km in the Strait of Georgia. Depths range from 5 m in coastal regions and rivers to over 700 m in Bute Inlet. The QCS model is currently under development. It has a larger extension, with its northern boundary well into Queen Charlotte Sound (around the latitude of Price Island) and the southern boundary in Johnstone Strait. Within the area of interest (Queen Charlotte Strait), resolution is between 50 and 500 m, while in other areas it increases up to 2 km. Model depths go from a minimum of 5 m to up to 700 m (e.g., at Seymour Inlet) and currently, the model has >120,000 nodes. Both the DI and QCS models are forced with six tidal harmonics (S2, M2, N2, K1, P1, and O1), river discharges, surface heating, and winds. We force the ocean boundary of the QCS model with outputs from the Coastal Ice Ocean Prediction System for the West coast (CIOPS-W). The model results will be evaluated against tide-gauge data as well as temperature, salinity and current meter data collected by DFO and other agencies.

We will assess whether there is a spatial scale limit for the usefulness of SWOT as a source of data to evaluate coastal models. In other words, we will understand whether we can use SWOT to evaluate the sea surface height at relatively open straits (~25 km wide) as well as in channels that are ~2 km wide (or even less).

2.2.3 Operational coastal ocean data assimilation

Here we build on existing operational data assimilation infrastructure at the Canadian Centre for Meteorological and Environmental Prediction (i.e. 1/4° resolution global and 1/12° resolution pan-Canadian regional configurations) and extend this capacity for coastal applications. A 1/36° resolution configuration for the Canadian east coast will be configured to extend research noted above (Section 1.1.2). This configuration will be used to quantify the spatial scales constrained using traditional nadir altimeters and the sensitivity to dynamic atmospheric corrections and long-wave error filtering. The potential benefits of using a multi-scale approach with scale-dependent background error covariances will be investigated. Simulated SWOT observations will be employed in an Observing System Simulation Experiment (OSSE) framework to investigate potential benefits and approaches to constrain submesoscale features. This will be followed by studies using the 1-day Cal/Val overpass along the Labrador Shelf to further investigate and demonstrate improvements of new approaches. Depending on the progress and success of the project a 1/36° configuration may also be setup for the Canadian west coast to exploit the 1-d Cal/Val overpass in that region.

2.3 Interactions between unbalanced and geostrophic flows

We will tackle this problem from two angles. On one hand, we will study the fundamental understanding of interactions between internal tides and slow motions in the (sub-) mesoscale. In the context of this particular project, “slow”, or (a) geostrophic, refers to balanced flow, and their extension into the submesoscale[1]. We will model the interaction with a hierarchy of shallow-water models (http://dedalus-project.org). It will allow us to identify which parameter regimes induce unpredictable phase shifts between the internal and astronomical tide, at the root of SWOT's inability to disentangle internal tides and (a) geostrophic flow. This project will also focus on the challenging coastal parameter regime where (a) geostrophic flows are the most non-linear and internal tides have the shortest wavelengths. The project will naturally evolve toward interactions of currents with three-dimensional bathymetries using either MITgcm (http://mitgcm.org) or Nek5000 (https://nek5000.mcs.anl.gov).

[1] Other authors might object to this terminology, which we use *ad hoc* here.

The second approach will be to seek practical ways to recognize spatial features, associated with either (a) geostrophic turbulence or internal tides, from snapshots. This approach would complement the fundamental understanding, sought in the first part of this project. If successful, it will provide useful results to the SWOT community in a short time frame. We will the potential of two sets of methods for retrieving information about the different modes of motion present in the data:

- Empirical Normal Modes (ENMs; Brunet & Vautard, 1996), which can be seen as "dynamics-aware Empirical Orthogonal Functions". In it, the search for the eigenvectors of the covariance matrix is replaced by the search for the eigenvectors of the matrix associated with a quadratic conserved quantity such as pseudo-energy or pseudo-momentum. In the atmosphere, the method has enabled the disentanglement of gravity waves vs. balanced flows in hurricanes (Martinez et al., 2011), a regime, similar to the submesoscale regime in the ocean.
- Machine learning (ML). A feasibility study has already shown promising results (Grisouard et al., *in prep*). We will tailor this method to SSH fields.

We have acquired training data from multiple sources ranging from idealized to realistic, some already published (Kelly, 2016; Dunphy et al., 2017), some generated locally in collaboration with B.K. Arbic (Univ. Michigan) and D. Menemenlis (NASA JPL), and output from the MITgcm LLC4320 simulation, available on Pangeo (Abernathey et al., 2017). If appropriate, we will use the "SWOT simulator" (Gaultier et al., 2016) to make these datasets closer to the expected rendering of SWOT, in order to assess the robustness of the methods. We will compare and contrast regions of high mesoscale variability (i.e. Gulf Stream) with regions of moderate mesoscale activity, in particular the northeast Pacific to add context to J.M. Klymak's project. Note that ENM and ML methods would both seek to obtain the same result. We hope that one would prove more efficient than the other, or that they would complement each other.

2.4 In situ observations of balanced and unbalanced motions

Here we propose to use shiptime during the Line-P monitoring program in the Northeast Pacific to observe submesoscale dynamics from the ship. The transect is 1,300 km long, from mouth of the Strait of Juan de Fuca to Station Papa at 50ºN, 145ºW and occupied three times a year (winter, early summer and late summer) allowing direct observation of the submesoscale under different seasonal conditions. Our measurement approach is described in Section 1.1.4 and will yield a statistical view of upper ocean-variability that will be directly comparable to observational products planned for SWOT. We will decompose the ADCP records into balanced and unbalanced motions using a Helmholtz decomposition, and subsequently into internal wave and non-internal wave motions with the addition of CTD data (Bühler et al., 2014; Callies et al., 2015). The northeast Pacific is a dynamically interesting place to carry out this work, due to the peculiar depth structure described in §1.1.4. The repeat seasonal sampling will allow us to determine the time history of the vorticity variance, and hence to test if it is driven by winter convection and the summer signals are fossils.

2.5 Projections of balance and imbalance on to SSH and how it is impacted by surface layer dynamics

In this modelling study, we examine SSH signatures of wind-driven balanced and unbalanced motions in the absence of tides. A large range of oceanographically-relevant flow regimes are considered in idealised numerical configurations.

Key issues that we address are the following: i) In what regimes do high frequency geostrophic modes contribute significantly to imbalance, ii) how should linearity of wave modes (and the lack thereof) be quantified and what is implied for their projection on to SSH and iii) how do surface layer dynamics (e.g., vertical resolution, turbulence parameterizations and explicit representation of the surface gravity wave field) impact the motion and its projection on to SSH. We proceed by using a very simple two-layer shallow water model (coupled to a slab embedded in the upper layer) to quickly explore parameter space and then follow up with high resolution simulations using the MITgcm. The bulk of our contribution will be to further explore these issues using high resolution simulations with the MITgcm. We will also assess the extent to which balanced and unbalanced contributions to SSH are altered by explicit representation of surface waves. For this part of the project, we are presently working to couple a surface wave model, WAVEWATCH III, to the MITgcm.

3. Anticipated Results

The proposal work addresses a number of the main oceanographic issues identified for the SWOT Science Team, i.e. Mesoscale ocean dynamics, Tides and High-frequency Motions, and Ocean State Estimation. It also addresses one of the synergistic science issues, i.e., Coastal/estuarine Studies.

It is anticipated that the project will lead to (1) improved knowledge of coastal currents, mesoscale features, tides, marine winds and waves in Canadian marine waters; (2) improved coastal and shelf models and operational prediction systems for circulation, tide and surface wave; (3) approaches that can effectively integrate simulated SWOT data into costal and shelf circulation models and methods that can detect sub-mesoscale eddies from SWOT SSH data, SAR observations, and SST and chlorophyll data from other satellites, as well as in situ drift measurements; and (4) improved understanding on the role of air-sea interactions in vertical mass/heat transport and on the submescoscale eddies on the air-sea interactions.

It is expected that the project will result in (1) a conceptual map of the parameter space that is conducive to internal tide scattering, transitioning to the first systematic study of the origins of coastal tidal incoherence; (2) innovative methods to process SWOT data, in the context of the data challenges that are being set up by the science team; (3) characterization of lateral variability in the Northeast Pacific, by comparison of internal-wave climatologies, quasi-geostrophic and frontogenesis theories; and (4) characterization of the midlatitude ocean regimes in which high frequency geostrophic modes contribute significantly to imbalance and the ageostrophic (ostensibly wave) portion of the flow should be treated as quasi-linear, as well as understanding of impacts of explicit representation of the surface gravity wave field on balance, imbalance, and their projections on to SSH.

References

Abernathey, Ryan, Kevin Paul, Joe Hamman, Matthew Rocklin, Chiara Lepore, Michael Tippett, Naomi Henderson, Richard Seager, Ryan May, and Davide Del Vento. 2017. “Pangeo NSF EarthCube Proposal.” doi:10.6084/m9.figshare.5361094.v1.

Bühler, O., Callies, J., & Ferrari, R. (2014). Wave–vortex decomposition of one-dimensional ship-track data. Journal of Fluid Mechanics, 756, 1007–1026. doi:10.1017/jfm.2014.488

Brunet, Gilbert, and R. Vautard. 1996. “Empirical Normal Modes versus Empirical Orthogonal Functions for Statistical Prediction.” *J. Atmosp. Sci.* 53 (23): 3468–89. doi:10.1175/1520-0469(1996)053<3468:ENMVEO>2.0.CO;2.

Callies, J., & Ferrari, R. (2013). Interpreting Energy and Tracer Spectra of Upper-Ocean Turbulence in the Submesoscale Range (1-–200 km). Journal of Physical Oceanography, 43(11), 2456–2474. doi:10.1175/JPO-D-13-063.1

Callies, J., R. Ferrari, J. M. Klymak, and J. Gula. 2015. “Seasonality in Submesoscale Turbulence.” *Nature Communications* 6: 6862. doi:10.1038/ncomms7862.

Capet, X., McWilliams, J. C., Molemaker, M. J., & Shchepetkin, A. J. (2008). Mesoscale to submesoscale transition in the California current system. Part I: Flow structure, eddy flux, and observational tests. *Journal of Physical Oceanography*, 38(1), 29–43. https://doi.org/10.1175/2007JPO3671.1.Carrere L., F. Lyard, M. Cancet, A. Guillot, N. Picot: FES 2014, a new tidal model - Validation results and perspectives for improvements, presentation to ESA Living Planet Conference, Prague 2016

Carrère, L., Le Provost, C., & Lyard, F. (2004). On the statistical stability of the M2 barotropic and baroclinic tidal characteristics from along-track TOPEX/Poseidon satellite altimetry analysis. J. Geophys. Res., 109(C3), C03033. doi:10.1029/2003JC001873

Chavanne, C., Flament, P., Luther, D., & Gurgel, K.-W. (2010). The Surface Expression of Semidiurnal Internal Tides near a Strong Source at Hawaii. Part II: Interactions with Mesoscale Currents*.

Journal of Physical Oceanography, 40(6), 1180–1200. doi:10.1175/2010JPO4223.1
Chen, C. R. H. Liu and R. C. Beardsley, 2003. An unstructured grid, finite volume primitive equation coastal ocean model: Application to coastal ocean and estuaries. *J. Atmos. Oceanic Technol.*, **20**, 159-186.
Chen, C., R. Beardsley, and G. Cowles, 2006. An unstructured grid, finite-volume coastal ocean model. FVCOM user manual, second edition, 315pp.
Chen Z., B. Zhang, Y. He, Z. Qiu, and W. Perrie, 2016: A new modulation transfer function for ocean wave spectra retrieval from X-band marine radar imagery. Chinese Journal of Oceanology and Limnology, doi: 10.1007/s00343-015-4147-1.
Colbourne, E., Holden, J., Snook, S., Han, G., Lewis, S., Senciall, D., Bailey, W., Higdon, J., and Chen, N. (2017). Physical oceanographic conditions on the Newfoundland and Labrador Shelf during 2016. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/079. v + 50 p.
Dong, C., G. Xu, G. Han, N. Chen, Y. He, D. Chen (2018). Identification of tidal mixing fronts from high-resolution along-track altimetry data. *Remote Sensing of Environment*, 209, 489-496.
Dupont, F., S. Higginson, R. Bourdallé-Badie, Y. Lu, F. Roy, G.C. Smith, J.-F. Lemieux, G. Garric, F. Davidson (2015). A high-resolution ocean and sea-ice modelling system for the Arctic and North Atlantic Oceans. *Geoscientific Model Development*, **8**, 1577-1594. doi:10.5194/gmd-8-1577-2015.
Dunphy, M., & Lamb, K. G. (2014). Focusing and vertical mode scattering of the first mode internal tide by mesoscale eddy interaction. Journal of Geophysical Research: Oceans, 119(1), 523–536. doi:10.1002/2013JC009293
Dunphy, Michael, Aurélien L. Ponte, Patrice Klein, and Sylvie Le Gentil. 2017. Low-Mode Internal Tide Propagation in a Turbulent Eddy Field. *Journal of Physical Oceanography* 47 (3): 649–65. doi:10.1175/JPO-D-16-0099.1.
Fu, L. L. (Ed), 2003, Wide Swath Altimetric Measurement of Ocean Surface Topography, Wide Swath altimeter working group, *JPL publication 03-2002*, JPL, California.
Fu, L.-L., and C. Ubelmann, 2014. On the transition from profile altimetry to swath altimeter for observing global ocean surface topography. *J. Atmos. Oceanic Technol.*, 31, 560–568, doi:10.1175/JTECH-D-13-00109.1.
Gaultier, L., U. Clement, and L.-L. Fu, 2016. The Challenge of Using Future SWOT Data for Oceanic Field Reconstruction. *J. Atmos. Oceanic Technol.*, 33, 119–126, doi:10.1175/JTECH-D-15-0160.1.
Gower, J., 2017: Cryosat-2 altimetry of BC Coastal Mountain glaciers. *Remote Sensing Letters*, 8:1, 21-28, DOI: 10.1080/2150704X.2016.1230280.
Grisouard, Nicolas, and Leif N. Thomas. 2015. “Critical and Near-Critical Reflections of near-Inertial Waves off the Sea Surface at Ocean Fronts.” *Journal of Fluid Mechanics* 765: 273–302. doi :10.1017/jfm.2014.725.
Grisouard, Nicolas, and Leif N. Thomas. 2016. “Energy Exchanges between Density Fronts and Near-Inertial Waves Reflecting off the Ocean Surface.” *Journal of Physical Oceanography* 46 (2): 501–16. doi:10.1175/JPO-D-15-0072.1.
Han, G., 2017. Altimeter Surveys, Coastal Tides, and Shelf Circulation. In: C.W. Finkl, C. Makowski (eds.), Encyclopedia of Coastal Science, DOI 10.1007/978-3-319-48657-4_7-2.
Han, G., N. Chen, C.Y. Kuo, C.K. Shum and Z. Ma, 2016: Interannual and decadal sea surface height variability over the Northwest Atlantic slope. *J-STARS*, DOI: 10.1109/JSTARS.2016.2584778.
Han, G., Z. Ma, B. de Young, M. Foreman, and N. Chen, 2011: Simulation of three-dimensional circulation and hydrography over the Grand Banks of Newfoundland. *Ocean Model.* 40, 199-210, https://doi.org/10.1016/j.ocemod.2011.08.009
Han, G., Z. Ma, N. Chen, N. Chen, J. Yang, and D. Chen (2017a). Hurricane Isaac storm surges off Florida observed by Jason-1 and Jason-2 satellite altimeters, *Remote Sensing of Environment*, 198, 244-153, **doi:/10.1016/j.rse.2017.06.005.**
Kelly, Samuel M. 2016. “The Vertical Mode Decomposition of Surface and Internal Tides in the Presence of a Free Surface and Arbitrary Topography.” *Journal of Physical Oceanography* 46 (12): 3777–

88. doi:10.1175/JPO-D-16-0131.1.
Li, H., and W. Perrie, 2016: Sea Ice Characterization and Classification Using Hybrid Polarimetry SAR. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, DOI: 10.1109/JSTARS.2016.2584542.
Li, H., Perrie, W., Li, Q., & Hou, Y., 2017a: Estimation of melt pond fractions on first year sea ice using compact polarization SAR. *Journal of Geophysical Research: Oceans*, 122, 8145–8166. https://doi.org/10.1002/ 2017JC013248.
Li, H., Jin Wu, W. Perrie, Yijun He, 2017b: Wind speed retrieval from hybrid-pol compact polarization Synthetic Aperture Radar images. *IEEE Journal of Oceanic Engineering*. 12 pages. Doi:10.1109/JOE.2017.2722225. accepted JUNE2017.
Liu, G., W. Perrie, V. Kudryavtsev, Y. He, H. Shen, B. Zhang, and H. Hu, 2016: Radar imaging of intense nonlinear Ekman divergence, *Geophys. Res. Lett.*, 43, 9810–9818, doi:10.1002/2016GL070799.
Liu, G., Perrie W. and C. Hughes (2017). Impacts of Ocean Surface Waves on Wind Power Input to the Mixed-Layer Near-Inertial Motions. 37(5). *J. Phys. Ocean.* doi.org/10.1175/JPO-D-16-0198.1.
Ma, Z., and G. Han, 2019: Reconstruction of the inshore Labrador Current from SWOT sea surface height measurements. *Remote Sensing*, Submitted.
Ma, Z., G. Han, B. de Young, 2015: Oceanic responses to Hurricane Igor over the Grand Banks: A modeling study. *J. Geophs. Res*., *120*, 1276-1295, https://doi.org/10.1002/2014JC010322.
Ma, Z., G. Han and B. deYoung, 2017. Modelling responses of Placentia Bay to hurricanes Igor and Leslie. Submitted to *Ocean Modelling*.
Martinez, Y., G. Brunet, M. K. Yau, and X. Wang. 2011. “On the Dynamics of Concentric Eyewall Genesis: Space–Time Empirical Normal Modes Diagnosis.” *J. Atmosp. Sci.* 68 (3): 457–76. doi:10.1175/2010JAS3501.1.
McWilliams, J. C. (2016). Submesoscale currents in the ocean. *Proceedings of the Royal Society of London A*, 472(2189), 20160117. https://doi.org/10.1098/rspa.2016.0117
Nash, J., Shroyer, E., Kelly, S., Inall, M., Duda, T., Levine, M., Jones, N., Musgrave, R. (2012). Are Any Coastal Internal Tides Predictable? Oceanography. doi:10.5670/oceanog.2012.44
Paquin, J.-P., Y. Lu, S. Taylor, H. Blanken, G. Marcotte, X. Hu, L. Zhai, S. Higginson, S. Nudds, J. Chanut, G.C. Smith, N. Bernier, F. Dupont (2019). High-resolution modelling of a coastal harbour in the presence of strong tides and significant river runoff. *Ocean Dynamics*, under review.
Ponte, A. L., & Klein, P. (2015). Incoherent signature of internal tides on sea level in idealized numerical simulations. Geophysical Research Letters, 42. doi:10.1002/2014GL062583
Qiu, Bo, S. Chen, P. Klein, J. Wang, H. Torres, L.-L. Fu, and D. Menemenlis. 2018. “Seasonality in Transition Scale from Balanced to Unbalanced Motions in the World Ocean.” *Journal of Physical Oceanography* 48 (3): 591–605. doi:10.1175/JPO-D-17-0169.1.
Rainville, L., & Pinkel, R. (2006). Propagation of Low-Mode Internal Waves through the Ocean. Journal of Physical Oceanography, 36(6), 1220–1236. doi:10.1175/JPO2889.1
Savva, Miles A. C., and Jacques Vanneste. 2018. “Scattering of Internal Tides by Barotropic Quasigeostrophic Flows.” *Journal of Fluid Mechanics* 856 (December): 504–30. doi:10.1017/jfm.2018.694.
Shriver, J. F., Richman, J. G., & Arbic, B. K. (2014). How stationary are the internal tides in a high-resolution global ocean circulation model? Journal of Geophysical Research: Oceans, 119(5), 2769–2787. doi:10.1002/2013JC009423
Smith, G.C., F. Roy, M. Reszka, D. Surcel Colan, Z. He, D. Deacu, J.-M. Belanger, S. Skachko, Y. Liu, F. Dupont, J.-F. Lemieux, C. Beaudoin, B. Tranchant, M. Drévillon, G. Garric, C.-E. Testut, J.-M. Lellouche, P. Pellerin, H. Ritchie, Y. Lu, F. Davidson, M. Buehner, M. Lajoie and A. Caya (2015). Sea ice Forecast Verification in the Canadian Global Ice Ocean Prediction System. *Quarterly Journal of the Royal Meteorological Society*, 142, 659–671. doi: 10.1002/qj.2555
Taylor, Stephanne, and David Straub. 2015. “Forced Near-Inertial Motion and Dissipation of Low Frequency Kinetic Energy in a Wind-Driven Channel Flow.” *Journal of Physical Oceanography*, November, 151106072713008. doi:10.1175/JPO-D-15-0060.1

Therriault, J.-C., et al., 1998. Proposal for a northwest Atlantic zonal monitoring program, *Can Tech. Rep. Hydrogr. Ocean Sci.* **194**, 57 pp.
Torres, Hector S., P. Klein, D. Menemenlis, B. Qiu, Z. Su, J. Wang, S. Chen, and L-L. Fu. 2018. "Partitioning Ocean Motions Into Balanced Motions and Internal Gravity Waves: A Modeling Study in Anticipation of Future Space Missions." *Journal of Geophysical Research: Oceans* 123 (11): 8084–8105. doi:10.1029/2018JC014438.
Torres, H. S., P. Klein, L. Siegelman, B. Qiu, S. Chen, C. Ubelmann, J. Wang, D. Menemenlis, and L.-L. Fu. 2019. "Diagnosing Ocean-Wave-Turbulence Interactions From Space." *Geophysical Research Letters*, August, 2019GL083675. doi:10.1029/2019GL083675.
Wagner, G. L., G. Ferrando, and W. R. Young. 2017. "An Asymptotic Model for the Propagation of Oceanic Internal Tides through Quasi-Geostrophic Flow." *Journal of Fluid Mechanics* 828 (October): 779–811. doi:10.1017/jfm.2017.509
Wenegrat, J.O. and L.N. Thomas (2017). Ekman transport in balanced currents with curvature. Journal of Physical Oceanography, 47, 5, 1187-1203.
Young, W. R., & Ben Jelloul, M. (1997). Propagation of near-inertial oscillations through a geostrophic flow. Journal of Marine Research, 55(4), 735–766. doi:10.1357/0022240973224283
Zaron, E. D., & Egbert, G. D. (2014). Time-Variable Refraction of the Internal Tide at the Hawaiian Ridge. Journal of Physical Oceanography, 44(2), 538–557. doi:10.1175/JPO-D-12-0238.1
Zhai, L., Y. Lu, S. Higginson, F. Davidson, F. Dupont, F. Roy, J. Chanut, G. Smith (2015). High-resolution modelling of the mean flow and meso-scale eddy variability around the Grand Banks of Newfoundland. *Ocean Dynamics*, 65(6), 877-887.
Zhang, B., X. Li, W. Perrie, and Y. He (2015), Synergistic measurements of ocean winds and waves from SAR, *J. Geophys. Res. Oceans*, *120*, 6164–6184, doi:10.1002/2015JC011052.
Zhang, G. and Will Perrie 2018: Satellite Backscatter Features of Surface Currents in the Open Ocean during Typhoon Lan (2017). *Remote Sensing*, 10, 875, doi.org/10.3390/rs10060875.
Zhang, G., Perrie, W., Zhang, B., Khurshid, S., & Warner, K., 2018: A Semi-empirical Model of the Ocean Surface for RADARSAT Constellation Mission Compact-Polarimetry SAR[J], *Remote Sensing of Environment*, Ref.: RSE-D-18-00116.