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Coastal Ocean Forecasting Science supported by GODAE OceanView Coastal Oceans and Shelf Seas Task Team (COSS-TT)—Part II

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1 Introduction

The regional and coastal ocean, as a complex interface area where land, hydrology, atmosphere and ocean interact, concentrates a wide range of actors dealing with increasing socio-economic and environmental issues. Under the pressure of the impacts of climate change, forecasting the coastal ocean remains a key challenge.

The international Coastal Ocean and Shelf Seas Task Team (COSS-TT) community within the OceanPredict program (former GODAE OceanView - https://www.godae-oceanview.org/) fosters multidisciplinary research efforts dedicated to the coastal ocean from the land/ocean interface to the shelf/open ocean exchange regions, in support of regional and coastal ocean forecasting. Following the first topical collection (De Mey et al. 2017), this second one offers research conducted within the COSS-TT themes.

After a successful 6th international COSS-TT meeting in 2018, new steps were outlined in the integration of knowledge and capabilities in regional and coastal ocean forecasting. Two major community events defined these next steps for ocean prediction (GODAE OceanView Symposium 2019 - OceanPredict '19 - http://oceanpredict19.org/) and ocean observation (OceanObs'19 - http://www.oceanobs19.net/). The OceanObs'19 conference called for the global ocean observing community and users to "advance the frontiers of ocean observing capabilities from the coast to the deep ocean... at the boundaries between the ocean and air, seafloor, land, ice, freshwater, and human-populated areas" and to "improve the uptake of ocean data in models for understanding and forecasting of the Earth system". These statements emphasize the need to improve the synergy between model and observations to develop regional and coastal ocean observing and forecasting capabilities (De Mey-Frémaux et al. 2019; Davidson et al. 2019). These 2018-2019 initiatives are well aligned to the scientific foundation of the United Nations Decade of Ocean Science for Sustainable Development (2021-2030). The COSS-TT community appears as a key actor of Ocean Decade Challenges related to regional and coastal ocean prediction (for example CoastPredict: Observing and Predicting the Global Coastal Ocean - https://www.coastpredict.org/).

In this framework, the COSS-TT community centered this second topical collection around scientific priorities in agreement with ongoing open research fields and new identified priorities (in **bold** are addressed priorities in this second topical collection): (a) advances in integrated, multi-platform, long-term **monitoring of physical, geochemical and biological parameters in coastal regions and coastal observatories**; (b) **development of fine-scale coastal ocean models**; (c) **downscaling approaches from large-scale to regional and coastal-scale models** (methods for quantitative assessment, regional and coastal array design, downscaling approaches and data assimilation and predictability in coastal ocean forecasting systems); (d) coastal-scale atmosphere-wave-ocean couplings, (e) **ecosystem response to physical drivers**; (f) probabilistic approaches and risk assessment in the coastal ocean (including extreme events, impact and signature of climate change, science in support of the mitigation of coastal hazards); (g) science in support of applications in coastal oceans and (h) synergy between coastal modelling and coastal altimetry.

2 Themes

2.1 Advances in integrated, multi-platform, long-term monitoring of physical, geochemical and biological parameters in coastal regions and coastal observatories

The analysis of parameters obtained from coastal observatories is a crucial activity not only for the understanding of the processes involved, but also for the assessment and improvement of the coastal ocean forecasting systems. In this context, Freitas et al. (2019) evaluated the role of high-frequency processes in the variability of continental shelf-slope currents. More specifically, the authors focused on near-inertial oscillations (NIO), which are intermittent motions with a frequency close to the inertial frequency and may represent an important fraction of the energy to the currents in the upper ocean. To characterize NIO, these authors used hourly *in situ* velocity records at 6 different locations along the Brazilian continental shelf break (16°S–31.5°S) describing the spatial variability of inertial energy in the mixed layer and the role of the NIO in the high-frequency hydrodynamic. The authors showed that near-inertial energy can represent up to 31% of the variance of the currents with absolute values of the near-inertial currents ranging between 5 - 50 cm s^{-1}, with values decreasing toward lower latitudes locations. Vertical shear of the order of 10^{-3} s^{-1} was reached during NIO events in the upper layer of the ocean and can play an important role in the vertical mixing along the Brazilian continental shelf break. The NIO events analyzed at the Cabo Frio upwelling system exhibited a mean duration of around 7.6 days, upward vertical phase velocity of the order of 10^{-1} cm s^{-1}, vertical wavelengths of the order of 102 m, and vertical downward group velocity of the order of 10^{-2} cm s^{-1}, demonstrating the importance of NIO as a source of kinetic energy to the ocean interior.

In the western boundary current system of the Bay of Bengal (BoB), in the Indian Ocean, Francis et al. (2020) examined the structure and variability of undercurrents in the East India Coastal Current (EICC) and the mechanisms of their formation. The authors used current data collected at 4 different locations and simulations for the period 2013–2014 from a high-resolution model configured for the BoB. The undercurrents were observed at all these locations, mainly during summer (June–August) and winter (October–December). Undercurrents were seen varying from relatively shallow depths (75 m) to deeper depths (100–150 m). The intraseasonal variability of undercurrents near the shelf break, in some regions, was directly linked to intraseasonal variability in the strength of surface EICC itself. Based on numerical simulations, these authors also investigated the interaction of eddies with the surface and subsurface flows.

These two studies used *in situ* observations associated with dedicated numerical simulations to illustrate the advances done in recent years to deploy integrated systems, which allowed significant progress in coastal/regional ocean process understanding necessary for forecasting.

2.2 Development of fine-scale coastal ocean models

In the framework of the development and implementation of fine-scale coastal ocean models, Marta-Almeida et al. (2019) present a very high-resolution modeling configuration to represent shelf-estuary interactions. Their application is on the estuary of Baía de Todos os Santos – BTS, Brazil (300 to 400 m), and adjacent coastal waters (600 to 1200 m). The adoption of a multi-corner domain approach allowed the variable spatial resolution required to resolve the shelf, the bay, and their interactions. This long-term simulation (seven years) uses realistic oceanic, atmospheric, and riverine forcings. The assessment of the model against observations shows the model's skill to reproduce the thermohaline field, the tidal currents, as well as the variability of the free surface at tidal and sub-tidal time scales. These results provide the first representation of the tidal wave propagation along the bay, in terms of maps of amplitudes, phases, and ellipses of the barotropic currents for the main tidal constituents. In addition, long-term residual currents (up to up to 0.5 m s^{-1}) at different depths highlighted several prominent structures that were identified and named. This model set-up proved to be highly efficient and robust simulating the BTS shelf-estuary region and such an approach may be suitable to other estuarine systems.

In Japan, Sakamoto et al. (2019) examined the impact of high resolution on model predictability. Using a 2-km resolution model, they expanded the coastal ocean monitoring and forecasting system of the Japan Meteorological Agency (JMA) from the Seto Inland Sea to the entire coastal seas of Japan. The authors used a 4-year hindcast experiment without data assimilation to assess the model performance, which realistically reproduced basic distributions, transports through the main Japanese straits, and seasonal variations of parameters including sea surface temperature, salinity, and sea level. Small-scale features in the coastal seas, such as fronts, were also well simulated due to the high resolution. This work was the first step and demonstration before introducing a high-resolution model in the coastal ocean monitoring and forecasting system of the JMA.

In the context of Canada's Ocean Protection Plan (OPP), Paquin et al. (2020), to enhance marine safety and emergency response capacity in the aquatic environment, improved the coastal and near-shore modeling capability by using the Nucleus for European Modelling of the Ocean (NEMO) model to develop an ocean forecasting system for Saint John harbor in the Bay of Fundy, on the east coast of Canada. The region is characterized by the presence of some of the world's strongest tides, significant river runoff, and complicated geometry. A three-level one-way nesting (resolutions of 2.5 km, 500 m, and 100 m, respectively) approach was used to downscale from a 1/12° North Atlantic-Arctic regional model to a very-high-resolution port-scale around Saint John harbor. Evaluation with observational data demonstrates the model's accuracy for the simulation of tidal elevation and currents, non-tidal water level and currents, temperature, and salinity. Virtual Lagrangian trajectories based on the modeled surface currents including wind effects were coherent with the observed trajectories of different types of surface drifters. Overall, this study highlights the capability of NEMO modeling framework to provide very-high-resolution modeling at port-scale resolution.

In a process-oriented approach, the interactions between barotropic tides and mesoscale processes were addressed by Stanev and Ricker (2020). Their research area covered part of the East Atlantic Ocean, a steep continental slope, and the European Northwest Shelf. The authors showed that tides affected the baroclinic fields at much smaller spatial scales than the barotropic tidal scales and changes in the horizontal patterns of the M_2 and M_4 tidal constituents provided information about the two-way interactions between barotropic tides and mesoscale processes. The interaction between the atmosphere and ocean measured by the work done by the wind was also affected by the barotropic tidal forcing. Tidal forcing intensified the transient processes and resulted in a substantial transformation of the wavenumber spectra in the transition areas from the deep ocean to the shelf. Tides flattened the sea-surface height spectra down to ~ $k^{-2.5}$ power law, thus reflecting the large contribution of the processes in the high-frequency range compared to quasi-geostrophic motion. The spectra along sections parallel or normal to the continental slope differ from each other, which indicates that mesoscale turbulence was not isotropic. An analysis of the vorticity spectra showed that the flattening was mostly due to internal tides. Compared with the deep ocean, no substantial-scale selectivity was observed on the shelf area. Particle tracking showed that the lengths of the Lagrangian trajectories increased by approximately 40% if the barotropic tidal forcing was activated, which contributed to changed mixing properties. The ratio between the horizontal and vertical scales of motion varied regionally depending on whether barotropic tidal forcing was included. The overall conclusion is that the barotropic tides affect substantially the diapycnal mixing.

Increasing spatial resolution and nesting model configurations are two areas of development that show a significant impact on the efficiency of numerical models that are part of coastal ocean forecasting systems.

2.3 Downscaling the ocean estimation problem from large-scale and regional-scale to coastal-scale models, data and forcings, including coastal data assimilation

While there is a natural overlap between this theme and the one just described above (e.g. Marta-Almeida et al. (2019) and Paquin et al. (2020) also adopted a downscaling strategy) the intention here is to focus on the techniques that can be used to improve the regional and coastal forecasting systems. For instance, Sakamoto et al. (2019) in addition to expanding the domain, as described in the previous section, also introduced some new dynamical elements. One of the major updates was the implementation of explicit tides with high precision, leading to amplitude and phase errors for the M_2 tide of only 9.2% and 10.2°, respectively. The second was a coupling of a sea ice model reproducing the seasonal development of sea ice in the Sea of Okhotsk. The third was the introduction of approximately 4000 river inflows across Japan to improve salinity in coastal seas. The introduction of the inverse barometer effect and high-resolution atmospheric forcings also contributed to coastal sea-level variations. In Paquin et al. (2020), one of the implementations for Canada's OPP due to the lack of accurate runoff data at the Saint John River outlet was the modification of the model's lateral open boundary condition to introduce the river forcing with the observed time series of water level near the mouth of the river.

In parallel with Sakamoto et al. (2019), Hirose et al. (2019) developed a new system to monitor and forecast coastal and open-ocean states around Japan for operational use by the JMA. The system consists of an eddy-resolving analysis model based on four-dimensional variational assimilation and a high (2-km) resolution forecast model covering Japanese coastal areas that incorporates an initialization scheme with temporal and spatial filtering. Assimilation and forecast experiments were performed for the period from 2008 to 2017, and the results were validated against various observation datasets. The assimilation results captured well the observed variability in sea surface temperature, coastal sea level, volume transport, and sea ice. Furthermore, the volume budget for the Japan Sea was significantly improved by the use of the 2-km resolution forecast model compared with the previous 10-km resolution analysis model. The forecast results indicate that this system has a predictive limit longer than 1 month in many areas, including in the Kuroshio Current area south of Japan and the southern Japan Sea. In the forecast results of case studies, the 2017 Kuroshio large meander was well predicted, and warm water intrusions accompanying Kuroshio path variations south of Japan were also successfully reproduced. Sea ice forecasts for the Sea of Okhotsk largely captured the evolution of sea ice in late winter, but sea ice in early winter showed relatively large errors. This system has a high potential to meet operational requirements for monitoring and forecasting ocean phenomena at both open ocean and coastal scales.

At the Western Mediterranean Sea, Aguiar et al. (2020) evaluated the impacts of downscaling the 1/16º (~6–7 km) Copernicus Marine Environment Monitoring Service (CMEMS) Mediterranean reanalysis. They focused on improving the surface circulation and mesoscale activity and downscaled the CMEMS model solution into a high-resolution 2-km free-run simulation. The use of multi-platform observations from satellite-borne altimeters, high-frequency radar, fixed moorings, and gliders provided insights into the variability from basin to coastal scales. Their results show that the downscaling leads to an improvement of the time-averaged surface circulation, especially in the topographically complex area of the Balearic Sea. In particular, the path of the Balearic current is improved in the high-resolution model, also positively affecting transports through the Ibiza Channel. While the high-resolution model produces a similar number of large eddies as CMEMS Mediterranean reanalysis and altimetry, it generates a much larger number of small-scale eddies. Looking into the variability, in the absence of data assimilation, the high-resolution model is not able to properly reproduce the observed phases of mesoscale structures, especially in the southern part of the domain. This negatively affects the representation of the variability of the surface currents interacting with these eddies, highlighting the importance of data assimilation in the high-resolution ocean model in this region to constrain the evolution of these mesoscale structures.

Downscaling is a critical issue for regional and coastal modeling systems since it also includes the estimation of propagating processes (e.g. tides, internal waves, Coastal Trapped Waves) with a wide range of temporal and spatial scales. It is important to remind that wave propagation through the boundaries of a downscaled model is a complicated topic, since the dynamics, to propagate those signals, might be absent in the parent model. In this topical collection, this issue has been addressed for different regions with focuses on different processes. Results confirm the sensitivity of the system to the downscaling strategy and possible improvements when those open boundary problems are considered carefully.

2.4 Ecosystem response to the physical drivers

Satellite data of both physical properties as well as ocean color can be assimilated into coupled ocean-biogeochemical models to improve the model state. Physical observations like sea surface temperature are usually better understood and therefore have smaller errors than ocean color, but it is unclear yet how efficiently they can constrain the biogeochemical model variables. Goodliff et al. (2019) evaluate the effect of assimilating satellite sea surface temperature in the coastal ocean-biogeochemical model HBM-ERGOM with nested model grids in the North and Baltic Seas. A weakly and strongly coupled assimilation is performed with an ensemble Kalman filter. For the weakly coupled assimilation, the assimilation only directly influences the physical variables, while the biogeochemical variables react only dynamically during the 12-hour forecast phases in between the assimilation times. For the strongly coupled assimilation, both the physical and biogeochemical variables are directly updated by the assimilation. The strongly coupled assimilation is assessed in two variants using the actual concentrations and the common approach to use the logarithm of the concentrations of the biogeochemical fields. Compared to the weakly coupled assimilation, the strongly coupled assimilation leads to stronger changes in the biogeochemical model fields. The experiments further indicate that for the strongly coupled assimilation of physical observations the biogeochemical fields should be used with their actual concentrations rather than the logarithmic concentrations.

The multi-disciplinary integrated approach because of applications in coastal oceans is one of the priorities of the COSS-TT community.

3 Outlook

While most of the articles included in this second topical collection can contribute to the development of applications in coastal oceans, it is important to emphasize the direct use of the developments implemented in the Coastal Ocean Forecasting Systems described here, which include the works of Goodliff et al. (2019), Hirose et al. (2019), Marta-Almeida et al. (2019), Aguiar et al. (2020), Sakamoto et. al. (2020), and Paquin et al. (2020).

The COSS-TT community is a constantly growing community that among other purposes seeks: i) to design and implement an integrated river/estuarine/coastal/open ocean observing and modeling multidisciplinary system and ii) to improve coastal marine forecasting and extended range predictive capabilities for the regional and coastal ocean. With a strong engagement and alignment with the *Decade of Ocean Science for Sustainable Development*, COSS-TT, via CoastPredict, fosters innovative and sustainable applications for coastal solutions/services that directly benefit local populations.

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