



Model-Observations Synergy in the Coastal Ocean

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Integration of observations of the coastal ocean continuum, from regional oceans to shelf seas and estuaries/deltas with models, can substantially increase the value of observations and enable a wealth of applications. In particular, models can play a critical role at connecting sparse observations, synthesizing them, and assisting the design of observational networks; in turn, whenever available, observations can guide coastal model development. Coastal observations should sample the two-way interactions between nearshore, estuarine and shelf processes and open ocean processes, while accounting for the different pace of circulation drivers, such as the fast atmospheric, hydrological and tidal processes and the slower general ocean circulation and climate scales. Because of these challenges, high-resolution models can serve as connectors and integrators of coastal continuum observations. Data assimilation approaches can provide quantitative, validated estimates of Essential Ocean Variables in the coastal continuum, adding scientific and socioeconomic value to observations through applications (e.g., sea-level rise monitoring, coastal management under a sustainable ecosystem approach, aquaculture, dredging, transport and fate of pollutants, maritime safety, hazards under natural variability or climate change). We strongly recommend an internationally coordinated approach in support of the proper integration of global and coastal continuum scales, as well as for critical tasks such as community-agreed bathymetry and coastline products.

Keywords: coastal, ocean, observations, models, synergy, synthesis, assimilation, array design

INTRODUCTION

The main interface between humans and the ocean occurs in the coastal seas. Major marine industries thrive in this area while citizens make daily use of the coastal ocean for recreation. OceanPredict (formerly GODAE OceanView; Davidson et al., 2019) promotes the proper integration of all ocean scales under an international, operational, data-assimilative, multi-nested modeling framework. A Coastal Ocean Forecasting System (COFS), often targeted toward operational use, involves a combination of appropriate coastal observing and modeling systems (e.g., Kourafalou et al., 2015a; De Mey et al., 2017). The resulting value chain comprises observations made at sea, satellite data, ocean forecasts and analyses providing specific products and services for end users.

Observing systems tend to be spatiotemporally sparse in coastal regions, in comparison to the small scales of ecosystem variability found there. A crucial observational challenge is addressing the variety of important spatial and temporal scales of the coastal continuum, i.e., the seamless transition from the deep ocean to estuaries, through the shelf: observations should sample the multiscale, two-way interactions of estuarine, nearshore, and shelf processes with open ocean processes, while accounting for the different pace of circulation drivers, such as the fast atmospheric and tidal processes and the slower general ocean circulation and climate scales, and for gradients of biological production, from mesotrophic estuaries to oligotrophic oceans.

To fully realize the benefits of coastal observing systems, observations and models must be better integrated within COFS. Observations can be used to guide coastal model development and assessment (see section “Using Observations to Guide Coastal Model Development and Assessment”). In turn, models can be used to connect and interpret sparse coastal observations (see section “Using Models to Connect and Interpret Sparse Coastal Observations”). Data assimilation (DA) and machine learning (ML) can provide quantitative, validated estimates of Essential Ocean Variables and parameters in the coastal continuum (see section “Using Coastal Models to Synthesize Observations”). Models and DA can also be used to design and optimize existing and future observational arrays, with implications on sampling technology and networks (see section “Using Models to Design and Optimize Coastal Observing Systems”).

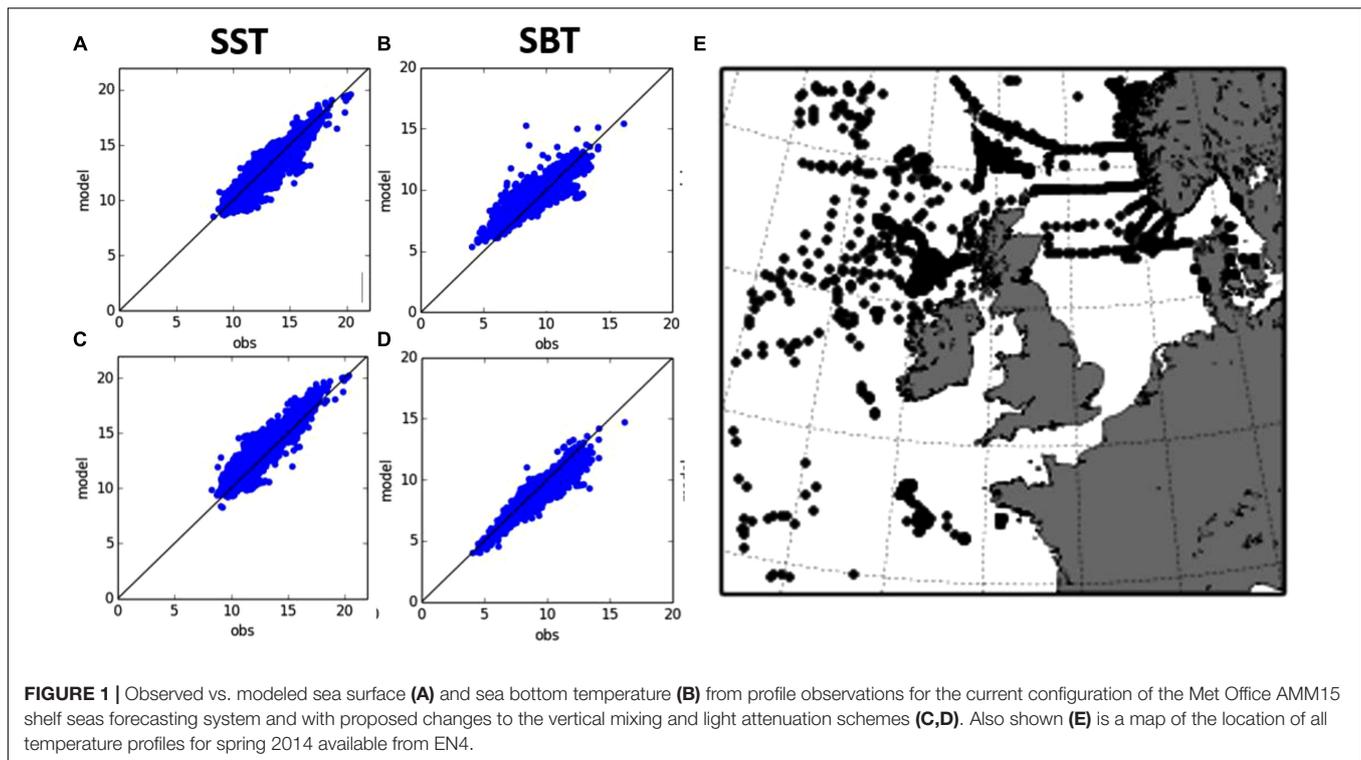
Integration of observations with models can add value to coastal observations and enable a wealth of applications, e.g., monitoring coastal sea-level rise (Ponte et al., 2019), decision-making support, marine search and rescue, coastal management under a sustainable ecosystem approach, aquaculture, dredging, transport and fate of pollutants, port operations, maritime and coastal populations safety, hazard analysis under natural variability and climate change. This paper focusses on how science can support coastal operational monitoring and forecasting to that end.

USING OBSERVATIONS TO GUIDE COASTAL MODEL DEVELOPMENT AND ASSESSMENT

Coupling models are a commonly used path when addressing the complex interactions between different components of the Earth System, but its assessment is challenging. One such example is illustrated by Staneva et al. (2016a,b, 2017) with a focus on the nonlinear feedback between strong tidal currents and wind-waves, which can no longer be ignored, in particular in the coastal zone where its role seems to be dominant. The inclusion of wave coupling appears to decrease strong winds through wave-dependent surface roughness (Wahle et al., 2017), and changes sea surface temperature, mixing and ocean circulation (Alari et al., 2016), leading to better agreement with *in situ* and satellite measurements. Comparisons with available atmospheric and oceanic observations also show that the use of the coupled system reduces the prediction errors in the coastal ocean especially under severe storm conditions.

Significant progress has occurred in operational model skill assessment in recent years (e.g., Hernandez et al., 2015). Sotillo et al. (2016) and Pascual et al. (2017) demonstrate the utility of using Lagrangian and multiplatform observations from a single extensive campaign to assess regional and coastal high-resolution models in the Alboran Sea. However, many coastal areas remain under-validated due to the shortage of observations. This affects variables such as surface currents, highly demanded by end-users for a widespread number of applications, while observational sources for currents are generally scarce and limited to High-Frequency (HF) radar-covered areas and some mooring stations. Wherever available, HF radars have been shown to be very beneficial for validating high-resolution regional ocean models (Oke et al., 2002; Liu et al., 2009; Wilkin and Hunter, 2013; Lorente et al., 2016a,b; Soto-Navarro et al., 2016; Mourre et al., 2018; Rodrigues, unpublished, 2015). In addition, reliable wave parameters can be inferred from the weaker second-order Doppler spectrum measured by the HF radar (Lorente et al., 2018).

To improve predictions in coastal regions, it is desirable to reduce biases in the models. However, the lack of both sub-surface observations and flux data in coastal regions severely hinders progress. An example of this problem is given by the shelf-seas model around the United Kingdom. Graham et al. (2018) demonstrated that increasing the horizontal resolution from 7 to 1.5 km led to improvements in off-shelf regions, but biases remained largely unchanged over the shelf region. In the North Sea, biases in both surface and bottom temperatures (Figures 1A,B) suggest that stratification errors are linked either to errors in surface forcing or to vertical processes. Experiments with vertical mixing schemes (Luneva et al., 2019) and light attenuation schemes (Figures 1C,D) suggest that changing these would reduce biases in bottom temperatures. However, there are no flux moorings in the North Sea to evaluate the surface forcing and very few (and infrequent) subsurface observations (Figure 1E) to evaluate the full depth seasonal cycle.



How valid are direct model-data comparisons? Small spatial scales and HF motions are a major challenge when comparing high-resolution model outputs to observations. Even when a model is deemed realistic, small phase errors can happen, with large consequences if strong gradients (e.g., fronts) are present. High-sampling rate time series are very valuable observations for model assessment or DA, but their representativeness when compared to model outputs remains questionable. This issue has been raised for coastal model assessment (e.g., Sandvik et al., 2016) and methods to overcome such a problem have been developed (e.g., “fuzzy” verification; Ebert, 2008). This may also call for specific strategies for the design of coastal observing networks.

USING MODELS TO CONNECT AND INTERPRET SPARSE COASTAL OBSERVATIONS

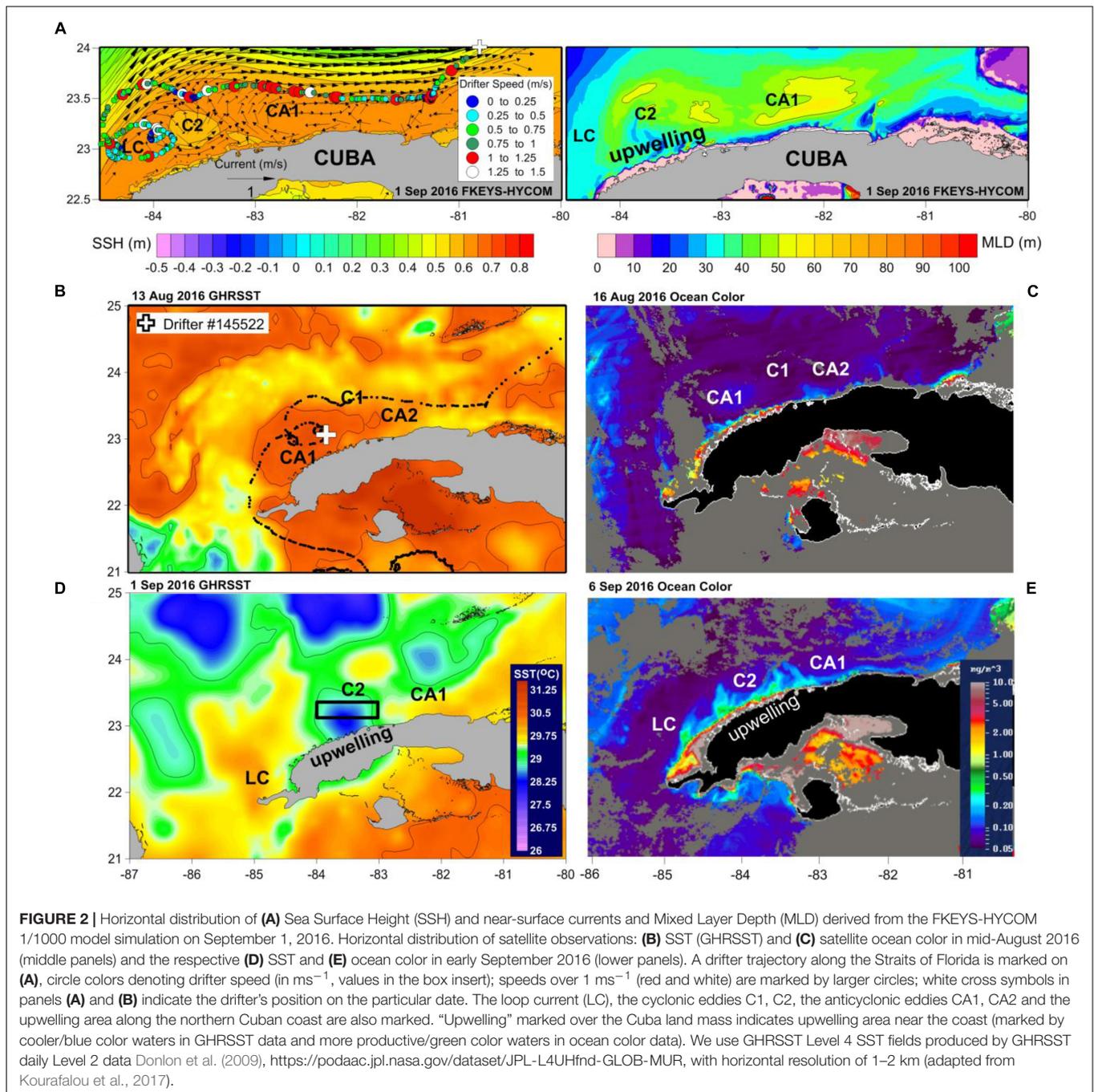
COFS must address the full spectrum of spatial and temporal scales in the coastal continuum. COFS must thus resolve interactions between nearshore, estuarine and shelf processes (target resolution: 10–100 m) and open ocean processes (target resolution: 1 km), preferably in a two-way mode. Approaches include downscaling and multi-nesting (e.g., Debreu et al., 2012; Kourafalou et al., 2015b; Trotta et al., 2017), upscaling (Schulz-Stellenfleth and Stanev, 2016), and unstructured-grid models (e.g., Zhang et al., 2016a,b; Federico et al., 2017; Stanev et al., 2017; Ferrarin et al., 2018; Maicu et al., 2018), and coupling with watersheds (Campuzano et al., 2016, 2018). These features make

those COFS more relevant to the interpolation and interpretation of sparse observations.

An example is given in Figure 2, off the northern coast of Cuba, an area of scarce availability in ocean data and the site of an eddy field which was found to play an important role on the broader regional mesoscale processes in the Gulf of Mexico. Kourafalou et al. (2017) describe the related processes using a high-resolution nested model (Kourafalou and Kang, 2012), satellite and *in situ* data. A series of cyclonic and anticyclonic eddies were identified along the Cuban coast in the Straits of Florida and were traced in model and observational data fields. The anticyclonic eddies were released from the Loop Current and progressed eastward, affecting the overall variability of the Loop Current/Florida Current system, a component of the Gulf Stream. The synthesis of model and observational data has led to a new understanding of the Gulf of Mexico’s mesoscale processes, with implications on the predictability of a major western boundary current.

The SAMOA Initiative (Alvarez Fanjul et al., 2018) uses such a synthesis of observation and model products to provide operational products and customized services for port operations in Spain. A suite of increasing-resolution models (down to ~100 m), involving wave modeling and improved metocean products, as well as dedicated observational field campaigns and near-real-time networks, is used to downscale CMEMS¹ products to coastal and port waters, providing enhanced products to end users.

¹CMEMS: Copernicus Marine Environment Monitoring Service, <http://marine.copernicus.eu/>.



USING COASTAL MODELS TO SYNTHESIZE OBSERVATIONS

Let us now turn to DA and ML approaches where models and observations are combined. DA (e.g., Moore and Martin, 2019) is traditionally complex and frustrating in coastal regions because of the multiple scales involved, and also because the data forcing is competing with open-boundary, riverine, and atmospheric forcings (the latter a DA product), which are often imperfectly known.

The value of assimilating HF radar observations to improve the coastal ocean state estimation (Oke et al., 2002; Wilkin et al., 2005; Barth et al., 2008; Shulman and Paduan, 2009; Stanev et al., 2015, 2016) or optimize boundary or surface forcings (Barth et al., 2011) has been demonstrated. Access to original radial radar measurements is important for assimilation (above references; Kurapov et al., 2003; Sperrevik et al., 2015). Reliable error variances and information on the spatially and temporally correlated error structure are very valuable (Vandenbulcke et al., 2016), but are unfortunately often unavailable.

Altimetry observations have recently been assimilated in shelf-sea systems, including operational systems (e.g., Sotillo et al., 2015; King et al., 2018). Although at an early stage compared with altimetry assimilation in global non-tidal models, use of these observations has the potential to better constrain the coastal mesoscale and the subsurface density structure. However, to derive the maximum benefit from these measurements, sub-surface temperature and salinity fields must already be reasonably well-constrained. The sparseness of profile observations in the shelf seas therefore adds to the challenge. With the upcoming launch of the SWOT wide-swath altimeter mission there will be a step-change in our ability to resolve the ocean mesoscale, but again challenges remain in making use of these low-temporal resolution observations, especially in dynamic shelf regions (cf. Gaultier et al., 2016; Bonaduce et al., 2018). For both nadir altimetry (e.g., Dibarboue et al., 2014) and future wide-swath missions, the complex budget of correlated errors at small scales ($< \sim 30$ km) is certainly the main difficulty to overcome.

High-frequency measurements are found to be complementary to altimetry (Pascual et al., 2015); together they provide a strong dynamical control for ocean models (Yu et al., 2012). Other studies also assimilate SST in addition to altimetry (e.g., Vervatis et al., 2016).

Ocean-color is affected by terrestrial organic matter and sediments in case II coastal waters, besides by phytoplankton pigments (IOCCG, 2000). The increased uncertainty of chlorophyll products needs to be accounted in assimilative shelf-sea ecosystem models (Ciavatta et al., 2016) or assimilation of alternative remotely sensed optical data could be considered to constrain biogeochemical simulations, e.g., light attenuation coefficients (Ciavatta et al., 2014) and remote sensing reflectance (Jones et al., 2016).

An important research area where observations and forecasts can be better integrated is related to the development of ML techniques. For instance, Chapman and Charantonis (2017) using iterative self-organizing maps managed to reconstruct the deep ocean currents of the Southern Ocean based on surface information provided by satellites. The algorithm was trained using satellite observations of surface velocity, sea-surface height and sea-surface temperature, as well as observations of the deep current velocity from autonomous Argo floats. ML techniques can also be used in conjunction with numerical models to improve the forecasts. For instance, Kalinic et al. (2017) presented an ocean forecasting system for ocean surface currents for the northern Adriatic coastal area based on self-organizing maps trained by a high-resolution numerical weather prediction model and HF radar data. O'Donncha et al. (2018) in a case-study site in Monterey Bay (California) integrated physics-based models to resolve wave conditions together with a ML algorithm that combines forecasts from multiple, independent models into a single “best-estimate” prediction of the true state. In another example, Wahle et al. (2015) applied a novel approach of DA based on Neural Networks to wave modeling in the German Bight; French et al. (2017)

combined artificial neural network with computational hydrodynamics for tidal surge inundation at estuarine ports in the United Kingdom to show that a short-term forecast of extreme water levels can achieve an accuracy that is comparable or better than the United Kingdom national tidal surge model.

USING MODELS TO DESIGN AND OPTIMIZE COASTAL OBSERVING SYSTEMS

Validated models can contribute to the efficient design and optimization of observing systems for science and operational uses (e.g., Fujii et al., 2019). Approaches include Observing System Simulation Experiments (OSSE), Observing System Experiments (OSE), and Objective Array Design (OAD) are able to handle heterogeneous, multi-platform observing systems: satellite-based, HF radars, buoys with low-cost sensors, autonomous vehicles, etc., OSSE and OSE need an assimilative system, while OAD does not (e.g., Le Hénaff et al., 2009; Charria et al., 2016; Lamouroux et al., 2016). Such approaches can be adopted in coastal regions to identify gaps in an existing observing network, to study operational failure scenarios, and to assess the potential of future observation types.

OSSE have been conducted in the last decade in the regional ocean (e.g., Halliwell et al., 2014, Halliwell et al., 2015; Aydođdu et al., 2018). One particular challenge is to develop a rigorous OSSE approach for the interaction of open-sea and coastal scales (with particular focus on coastal scales where observations are sparser and scales shorter) adopting multi-scale models as Nature Runs to back up synthetic observations (e.g., Oke et al., 2015; Fujii et al., 2019).

Using an OSE-type approach, Pein et al. (2016) investigated how salinity measurements in the Ems Estuary affect the reconstruction of the salinity field. Indeed, estuarine and strait dynamics (Stanev et al., 2018), largely dominated by tides and their interaction with buoyancy forcing, provide a new challenge to amalgamating observations and modeling. The approach helped to identify observation locations which are more suitable for model-data synthesis.

Based on existing observing technologies, the use of autonomous platforms (e.g., gliders) or systems deployed on ships of opportunity [e.g., FerryBox, Fishery Observing Systems (FOS)] is worth investigating. The impact of those solutions, identified in previous strategy plans (Morin et al., 2015), has been illustrated in several OSSE, OSE or OAD experiments. It has been shown that assimilating glider observations (hydrology but also velocity) in ocean models does improve modeling systems (e.g., Dobricic et al., 2010; Pan et al., 2011; Jones et al., 2012; Melet et al., 2012; Hernandez-Lasheras and Mourre, 2018). Deploying gliders in coordinated network configurations will further enhance the capacity of the modeling system to reproduce targeted dynamical features (Alvarez and Mourre, 2014). Moreover, long-term repeated glider missions along endurance lines were

shown to provide a new view of the ocean variability in narrow channels (Heslop et al., 2012) and in the transition zone between coastal and the open ocean (Rudnick et al., 2017). The HF sampling of surface coastal waters by FerryBox systems also delivers observations that improve assimilated model simulations (Korres et al., 2014; Stanev et al., 2016; Aydoğdu et al., 2018). Particularly, in waters where the ocean dynamics are tidally driven, the assimilating FerryBox will be more efficient than slower glider platforms (Charria et al., 2016). To fill gaps between glider tracks and FerryBox commercial lines, FOS appear as a valuable add-on to sample the water column and potentially improve operational predictions (Lamouroux et al., 2016). Aydoğdu et al. (2016) showed that those systems remain efficient even with a limited number of equipped ships if the spatial coverage is adapted to the region dynamics.

Due to the high spatial and temporal variability of the coastal patterns, the observations at the coastal scale may be deployed following an adaptive and relocatable strategy (e.g., autonomous vehicles: Ramp et al., 2009; Murre and Alvarez, 2012). The effort spent in the recent years to build relocatable model platforms (e.g., De Dominicis et al., 2014; Rowley and Mask, 2014; Trotta et al., 2016) can guide the optimization of this adaptive observing strategy. A recently successful autonomous vessel is the Offshore Sensing SailBuoy², which was used for directional wave measurements in the North Sea (Hole et al., 2016). Being 100% wind propelled, the SailBuoy has two-way communication via the Iridium network. It has been used for validation of ocean models and remote sensing observations, deployed both in the Arctic and the Gulf of Mexico (Ghani et al., 2014).

CONCLUDING REMARKS

Models can play a critical role in relation with coastal observations, at connecting sparse observations, synthesizing them, and assisting the design of observational networks. In turn, whenever available, observations can guide coastal model development for research and operational use.

To adequately represent the bidirectional interactions between the open ocean and small-scale processes, a better integration and coordination of coastal and large-scale observation systems would be beneficial. A promising combination would involve HF radars and reprocessed coastal altimetry data (Gommenginger et al., 2011).

Progress must be made in the next decade on coastal observations, in particular regarding surface currents, subsurface observations and flux data, and strategies must be developed to assess the smallest scales (plumes, fronts, plankton blooms, etc.). Likely upcoming breakthroughs will be Sentinel-3A wind, wave and optical measurements (Heslop et al., 2017; Pahlevan et al., 2017; Schulz-Stellenfleth and

Staneva, 2018; Wiese et al., 2018), synthetic aperture radar (SAR)-based wide-swath altimetry (SWOT), the WaCM mission (Rodriguez et al., 2019), and the SKIM³ mission, if approved. The availability of accurate, community-agreed bathymetry, reference levels and coastline products are also critical, since without them one cannot get HF processes right nor ensure consistency of coastal models with basin-scale models (e.g., Toubanc et al., 2018). The situation regarding freshwater fluxes and the monitoring of rivers is contrasted (Mishra and Coulibaly, 2009); neither river climatologies nor watershed models are fully satisfactory (Campuzano et al., 2016). Validated observational error estimates must also be a priority.

One of the challenges of coastal ocean observing systems in the next decades is the integration of new and conventional technologies to monitor the variability at small scales and through integration into multiplatform observing and forecasting systems (Tintoré et al., 2013). The establishment of coastal ocean observing systems is being implemented as an important component of marine strategy. These coastal observatories, such as the Integrated Marine Observing System (IMOS) in Australia, the Ocean Observing Initiative (OOI), and the Integrated Ocean Observing System (IOOS) in the United States, Neptune and Venus in Canada, the Coastal Observing System for Northern and Arctic Seas (COSYNA) Project in Germany, Poseidon in Greece, and SOCIB in Spain are today providing new quality controlled observational datasets following standard and international protocols.

New insights on coastal processes can be gained from the measurements of trace elements and isotopes. For instance, radium isotopes (Moore, 2000; Charette et al., 2016) have proven capable of tracing continental waters into the ocean from rivers, estuaries or submarine groundwater discharge.

Finally, coastal areas are ideal in engaging the public in current scientific challenges and raise their awareness on global environmental concerns of immense importance, including global warming and plastic pollution (Cigliano et al., 2015). Citizen science data collected in coastal areas have reached the quality appropriate for exploitation in marine policy (Hyder et al., 2015), coastal area monitoring (Brewin et al., 2015, 2017b) and scientific studies (e.g., for the evaluation of satellite data in coastal regions, Brewin et al., 2017a; Yang et al., 2018). Citizen science data can cover areas that are typically under-sampled by traditional monitoring networks (e.g., intertidal zone) and may offer new opportunities for a quantitative evaluation or assimilation into coastal models. Citizen feedback can even be useful in guiding future observation strategies and model development. Engaging citizens can improve ocean literacy, providing support for future coastal monitoring and modeling (García-Soto et al., 2017). The delivery of sector-focused operational products and services (e.g., Heslop et al., 2019) will progressively allow exploiting and help in developing the full potential of our present

²www.sailbuoy.no

³<https://www.skim-ee9.org/>

coastal ocean observing and forecasting capabilities. This will allow in turn receiving the necessary feedback from the user communities to guide future observation and evolution strategies.

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AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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