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Solving Coastal Dynamics: Introduction to High Resolution Ocean Forecasting Services

Joanna Staneva[1], Angelique Melet[2], Jennifer Veitch[3], Pascal Matte[4]

[1]Institute of Coastal Systems - Analysis and Modeling, Helmholtz-Zentrum Hereon, Geesthacht, Germany
[2]Mercator Ocean International, Toulouse, France
[3]Egagasini Node, South African Environmental Observation Network (SAEON), Cape Town, South Africa
[4]Meteorological Research Division, Environment and Climate Change Canada, Québec, QC, Canada

Correspondence to: Joanna Staneva (joanna.staneva@hereon.de)

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Abstract. Coastal services are fundamental for society, with approximately 60% of the world's population living within 60 km of the coast. Thus, predicting ocean variables with high accuracy is a challenge that requires numerical models able to simulate from mesoscale to submesoscale processes, to capture shallow water dynamics influenced by wetting-drying and resolve the ocean variables in very high-resolution spatial domains. This paper introduceskey aspects of coastal modelling, such as vertical structure of the mixed layer depth, parameterization of bottom roughness and the dissipation of kinetic energy in coastal areas. It stresses the need for models to account forthe nonlinear interactions between tidal currents, wind waves, and small-scale weather patterns, emphasizing their significance in refining coastal predictions. In addition, observational advancements, such as high-frequency (HF) radar and satellite missions like SWOT, provide unique opportunities to observe coastal dynamics. This integration enhances our ability to model physical and dynamical peculiarities in coastal waters, estuaries, and ports. Coastal models not only benefit from such high-resolution observations but also contribute to evolving observational systems, creating feedback loops that refine monitoring and prediction capabilities. Modeling strategies are also examined, including downscaling and upscaling approaches, and numerical challenges like implementing robust data assimilation schemes to refine estimations of coastal ocean states are addressed. Emerging techniques, such as advanced turbulence closure models and dynamic vegetation drag parameterization, are highlighted for their role in enhancing the realism of modeled coastal processes. Furthermore, the integration of atmospheric forcing, tidal asymmetries, and estuarine dynamics underlines the necessity for models that span the complexities of the coastal continuum. It also demonstrates the critical importance of accurately modeling coastal and estuarine systems to capture interactions between mesoscale and submesoscale processes, their connections to broader oceanic systems, and their implications for sustainable coastal management and climate resilience. This work underscores the potential of advancing coastal forecasting systems through interdisciplinary innovation, paving the way for enhanced scientific understanding and practical applications.

1 Introduction

High resolution observation and modelling are needed so that marine services can be compliant with small-scale processes in the ocean, particularly in coastal areas where these processes have a significant impact on dynamics and biogeochemistry (Figure 1). The importance of high resolution in coastal services is underscored by the coastal ocean's significance to humanity, not least because about 60% of the world's population lives within 60 km of the coast (Rao et al., 2008). These areas are highly dynamic, subject to both anthropogenic pressures, such as eutrophication, overfishing, offshore wind farm development, dredging, and pollution, and natural drivers, including sea-level rise, global warming, and changes in meteorological and hydrological conditions. These combined influences frequently trigger regime shifts, coastal erosion, flooding, and the introduction of invasive species, underscoring the vulnerability and complexity of these systems.

Accurately predicting ocean variables in coastal environments is challenging due to the need to resolve mesoscale to submesoscale dynamics and their interactions with atmospheric and hydrological processes. The inherent variability of these

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systems requires models that can account for a wide range of phenomena, including tidal asymmetries, wetting-drying cycles, nonstationary river and atmospheric forcing, and nonlinear feedback mechanisms between tidal currents and wind waves (Staneva et al., 2017). These processes influence mixing, ocean circulation, and the accuracy of sea surface temperature predictions. Thus, high-resolution models are indispensable for capturing the fine-scale interactions that drive coastal dynamics and shape biogeochemical responses.

Observational data play a pivotal role in advancing coastal modeling. High-frequency (HF) radar and novel high resolution satellite missions offer unprecedented opportunities to observe and understand coastal processes with fine spatial and temporal resolution (De Mey-Frémaux et al., 2019). These data sources are integral to improving the representation of physical and biogeochemical variability in models, bridging the gap between observations and predictive frameworks. By integrating data from remote sensing and in situ platforms, coupled with advanced data assimilation techniques, models can better capture the complexity of estuarine and nearshore processes.

Changes occurring in the coastal ocean are attributed to both direct human impacts and climate change. Human impacts encompass factors such as eutrophication, overfishing, offshore wind farm construction, dredging, and pollution. Natural changes in the coastal ocean result from sea-level rise, global warming, and alterations in meteorological and hydrological conditions such as precipitation, evaporation, wind patterns, and river run-off. These natural and human-induced changes can lead to significant regime shifts, including alterations in biogeochemistry, increased coastal erosion, heightened flooding risks, and the proliferation of invasive species, among other impacts.

Science-based services in the coastal ocean are essential for ensuring efficient management, sustainable use of coastal systems, and the development of strategies that are adaptable to the changing climate, including sea-level rise. These efforts, for example, align with the marine strategy framework directive in the European context (Hyder et al., 2015).

The aim of this paper is to introduce high-resolution ocean forecasting services that address the challenges of coastal dynamics by improving predictions of physical and biogeochemical processes. It focuses on the integration of advanced modeling techniques and modern observational tools to enhance understanding of small-scale dynamics and their connections to larger ocean systems. The paper first describes the spatial scales and processes that high-resolution models address, focusing on local, regional, and transitional zones. It then explores advanced observational tools, such as satellite missions and HF radars, and their role in improving coastal forecasts. Following this, the discussion highlights numerical modeling techniques, including turbulence modeling and bottom drag parameterization, which are essential for capturing small-scale coastal dynamics. It also examines the role of data assimilation techniques and observing system experiments in improving prediction accuracy and guiding the design of observation networks. Finally, the paper concludes with a summary of findings, identifies current challenges, and outlines future directions for advancing coastal forecasting systems. By addressing these topics, the paper aims to support the development of more robust and adaptable tools for coastal forecasting, which are critical for sustainable management and improving resilience to environmental changes.

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Figure 1: Schematic representation of the coastal zone, hazards (e.g. HAB (harmful algea bloom), metocean and biogeochemical variables, as well as observations and applications (adapted from Melet et al., 2020).

2 Typical spatial scales and processes solved by high-resolution services

High-resolution services in the coastal ocean operate at various spatial scales depending on the specific applications and objectives. These scales can range from local to regional levels, aiming to capture fine-scale processes and variations. Here are some typical spatial scales for high-resolution services:

1. Local Scale: At the local scale, high-resolution services focus on small coastal areas, such as individual bays, estuaries, or nearshore zones. These services aim to provide detailed information and predictions for specific locations of interest. Spatial resolutions in this range can be on the order of meters to a few kilometers, allowing for precise observations and modeling of localized processes.

2. Coastal Scale: High-resolution services at the coastal scale cover larger coastal regions, spanning multiple bays, estuaries, and coastal zones. These services provide a broader view of the coastal environment and its dynamics. Spatial resolutions in this range typically range from a few kilometers to tens of kilometers, enabling the capture of coastal- to regional-scale variations and interactions.

3. Transition Zones: Transition zones refer to areas where coastal and open ocean processes interact. These zones often exhibit complex dynamics and are of particular interest for high-resolution services. Spatial resolutions in transition zones can vary depending on the specific characteristics and objectives, but they generally aim to capture the intricate interactions between coastal and open ocean processes.

Eddies or isolated vortices, meandering currents or fronts and filaments are characteristic features of oceanic mesoscale processes. These processes typically exhibit spatial scales ranging from 10 to 500 kilometers, depending on geographic latitude

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and stratification, and time scales ranging from several days to approximately 100 days. Submesoscale processes in the ocean, on the other hand, are characterized by smaller scales, typically ranging from 1 to 10 kilometers (McWilliams, 2016). These scales are smaller than the Rossby radius of deformation. Submesoscale processes also have shorter temporal scales, usually lasting only a few hours, and their relative vorticity is greater than the Coriolis parameter f. In contrast, for mesoscale motion, the relative vorticity is comparable to f. Overall, studying and observing submesoscale processes require advanced techniques and methods to overcome their small scale and rapid variability, but their understanding is crucial for comprehending the intricate dynamics of the ocean.

The surface and bottom mixed layers in the open ocean occupy just a tiny part of the ocean volume because these layers are much thinner than the almost viscousless ocean interior. However, in the coastal zone, drag parameterizations become increasingly important in shallow water, and even more so where the impact of vegetation is significant. Furthermore, a large part of kinetic energy in the ocean is dissipated in the coastal zone, which necessitates an adequate modelling of this important small-scale process, vital for the global energy balance (Munk and Wunsch, 1998). To accurately represent the coastal dynamics and the fine structure of these layers, models need to resolve the vertical structure of the mixed layers. This requirement necessitates the use of turbulence closure models, which account for the effects of turbulence and mixing in these regions. Additionally, models for coastal processes need to consider the impact of bottom drag. The parameterization of bottom roughness, often based on the grain size distribution, allows for the inclusion of bottom drag effects. In cases where vegetation is present, drag parameterizations become even more important. A significant portion of the kinetic energy in the ocean is dissipated in the coastal zone. Therefore, it is crucial to adequately model these small-scale processes in order to maintain a balanced representation of the global energy dynamics. Understanding and accurately simulating the dissipation of kinetic energy in coastal areas contribute to a comprehensive understanding of the ocean's energy budget.

In shallow water, the variability of surface elevation caused by tides and storms becomes comparable to the water depth itself. In some coastal areas, shallow-water tides play a significant role in the overall tidal dynamics. To improve the accuracy of tidal predictions in shelf regions, it is necessary to consider higher harmonics and assess the ability of ocean models to fully resolve the tidal spectrum.

Some important processes, such as the nonlinear feedback between strong tidal currents and wind waves, cannot be ignored in the coastal zone (Staneva et al., 2016a, 2016b, 2017). Wave-current coupling tends to decrease strong winds through wave-dependent surface roughness (Wahle et al., 2017), affects mixing and ocean circulation, and improves predictions for sea surface temperature. Further examples of the value of the incorporation of coupling in the numerical models in the coastal ocean are given by De Mey-Frémaux et al. (2019). These scientific developments of operational oceanography are in pace with the trend in the Earth System modelling to seamlessly couple different environmental prediction components of atmosphere, waves, hydrology, and ice.

The small spatial scales characteristic of coastal and estuarine systems require coastal models to consider ageostrophic (deviating from the Earth's rotation) and three-dimensional dynamics, primarily driven by boundary-layer processes (Fringer et al., 2019). Understanding these small-scale processes is crucial, particularly the interactions between mesoscale and submesoscale dynamics and their connection to larger-scale processes. It is essential to improve the representation of exchanges between the coastal and open ocean, as well as their coupling with estuaries and catchment areas, in order to capture the complexity of coastal systems. Accounting for high-resolution atmospheric forcing into coastal models is essential for accurately capturing local meteorological dynamics, including wind patterns, temperature gradients, and precipitation rates. Such detailed atmospheric data drive fundamental processes like heat and momentum fluxes, profoundly influencing coastal hydrodynamics, sediment transport, and ecosystem responses. Coastal models need to accurately account for frictional balances, taking into consideration the effects of friction on the movement of water. They must also address wetting and drying processes, as well as hydrological forcing, to capture the transitions between shallow environments and larger regional scales. By incorporating these factors, models can provide a more realistic representation of coastal dynamics. In addition, the grid characteristics used in coastal models should be carefully selected to accurately represent the dominant spatial scales present in the coastal environment. Choosing grid resolutions that capture the essential features of the coastal system is crucial for obtaining reliable and meaningful results.

In the coastal ocean, characteristic time scales are significantly shorter compared to the global ocean. These time scales, typically around 1 day, are determined by various processes, including tides, inertial motion, diurnal cycles, and synoptic weather patterns. The fast-paced dynamics of the coastal ocean require models to accurately capture these shorter time scales. In estuaries, the periodicity becomes more complex due to strong tidal asymmetries and the presence of secondary circulation patterns. The interactions between tidal forcing, river flow and estuarine geometry result in intricate and variable periodic patterns. The periodicity observed in coastal seas is mainly influenced by external forcing signals, such as atmospheric conditions or remote ocean signals. These external signals propagate into coastal models through the specification of lateral boundary conditions, which is a crucial aspect of modeling in coastal areas. Unlike global models that can operate with open boundaries, coastal models require careful consideration of these boundary conditions to accurately represent the interactions between the coastal and open ocean.

The predictability limit of models depends on the geophysical processes. For synoptic processes in the open ocean, this limit is on the order of weeks to months. For the coastal ocean, it is on the order of hours to days. The loss of predictability, associated with nonlinear processes, is exemplified by the growth of errors in predictive models. Assimilation of data containing spatial and temporal scales below the predictability limit is needed to address this issue. Simulations at grid resolutions that would sufficiently resolve the coastal submesoscale would require horizontal grid resolutions of approximately 1-10 meters in estuaries and 0.1-1 kilometer in coastal shelf domains. However, achieving such high resolutions poses significant computational challenges and resource demands.

By employing high-resolution services with appropriate spatial scales, scientists and stakeholders can gain a more detailed and accurate understanding of coastal processes, improve forecasting capabilities, and support effective coastal management and decision-making.

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3 State-of-the-art data and tools for coastal forecasting

3.1 Required observations

Observing systems are spatiotemporally sparse in coastal regions compared to the small scales of ecosystem variability found there. A crucial challenge in observations is addressing the variety of important spatial and temporal scales within the coastal continuum, which encompasses the seamless transition from the deep ocean to estuaries through the shelf. In order to achieve this, observations should sample the multiscale, two-way interactions of estuarine, nearshore, and shelf processes with open ocean processes. Additionally, they need to account for the different pace of circulation drivers, such as fast atmospheric and tidal processes, as well as the slower general ocean circulation and climate forcing. It is also important to accurately sample the gradients of biological production, ranging from mesotrophic estuaries to oligotrophic oceans. Given the current situation, observational practices and strategies need to be strongly coupled with numerical modeling to effectively extract the information contained in the data and advance the quality of coastal services.

Most global and regional prediction products use a combination of satellite observations and in situ observations. Traditionally, in situ observations constituted the major data source for coastal ocean monitoring. During the end of the past century, satellite observations contributed significantly to the understanding of spatial variabilities. Novel instruments, such as the acoustic Doppler current profiler (ADCP), which measures current profiles throughout the water column, enhanced our understanding of current shear and bottom stress. Nowadays, high-resolution numerical simulations in the coastal ocean are keeping pace with high-resolution observations. A similar trend is observed in coastal waters, estuaries, and ports, which are rich in different activities and interests: fishing, recreational activities, search and rescue, protection of habitats, storm forecasts, maritime industries, as well as routine maintenance operations (De Mey-Frémaux et al., 2019).

The coastal ocean observations only are not sufficient to fully support the present-day need for high-quality ocean forecasting and monitoring because measurements may represent very localized and short scale dynamics, and it is not straightforward to know how fully they describe the complex coastal system. Therefore, recent practices employ the synergy between observations and numerical modeling, which ensures valuable research advancements and practical implementations (Kourafalou et al., 2015a, 2015b). The core components of operational oceanographic systems consist of a multi-platform observation network, a data management system, a data assimilative prediction system, and a dissemination/accessibility system (Kourafalou et al., 2015a; De Mey-Frémaux et al., 2019; Davidson et al., 2019). By combining observations and models through data assimilation methods, ranging from coastal to global and from in situ to satellite-based, we can assess ocean conditions and create reliable forecasts. This integration adds value to coastal observations and enables a wide range of applications (De Mey-Frémaux et al., 2019; Ponte et al., 2019), as well as providing decision-making support. For a comprehensive review of ocean monitoring and forecasting activities in both the open and coastal oceans, please refer to Siddorn et al. (2016).

High-frequency radars (HFR) offer unique spatial resolution by providing reliable directional wave information and gridded data of surface currents in almost real time. The use of HFR networks has become an essential element of coastal ocean

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observing systems, contributing to high-level coastal services (Stanev et al., 2016; Rubio et al., 2017). The outputs from prediction systems extend the utility of HFR observations beyond the immediate observation area (Stanev et al., 2015), enabling adequate estimates even where no direct observations have been made. This demonstrates how models connect observations, synthesize them, and assist in the design of observational networks. In turn, observations can guide the development of coastal models (De Mey-Frémaux et al., 2019).

Alongside ADCP data, HFR data are used for skill assessment of operational wave and circulation models (Lorente et al., 2016). Another valuable source of fine-resolution data in the coastal region is provided by color data from satellites. In terms of sea level observations, some challenges associated with the use of altimeter data in the coastal zone are expected to be overcome through the use of wide-swath Surface Water and Ocean Topography (SWOT) technology. SWOT provides two-dimensional observations of sea surface topography at kilometer resolution in a 120 km swath. The expectation is that wide-swath altimetry will significantly enhance the quality of coastal ocean forecasts through high spatial coverage and resolution. These new data are anticipated to (1) sample the two-way interactions between nearshore, estuarine, and shelf processes and open ocean processes, and (2) resolve both fast processes (atmospheric, hydrologic, tidal) and slower processes (general ocean circulation and climate evolution). High-resolution models play a critical role as integrators of these coastal continuum observations.

3.2 Numerical models

Addressing specific processes in the coastal ocean and accurately modeling the transition between regional and coastal scales cannot be achieved solely by adjusting the model resolution. Certain processes, such as shallow-water tides, which are often overlooked in global and regional forecasting, play a dominant role in coastal ocean dynamics. The previous sections have highlighted the importance of a tailored approach in observational practices and numerical models for the coastal ocean. For further information on other popular coastal models, refer to the comprehensive discussion by Fringer et al. (2019).

Table 1: Circulation models in alphabetical order, which can be used for coastal and regional studies and/or provision of services.

Model	**Citationan**	**C: Coastal, R: Regional, G: Global**	**Finte-volume (FV) or Finite-element (FE)**
ADCIRC	Luettich et al. (1992) Westerink et al. (1994)	C	FE
COAWST	Warner et al. (2008, 2010)	C/R	FV
CROCO	Marchesiello et al. (2021)	R	FV
Delft3D	Delft3D-Flow User Manual (2024)	C	FV
FVCOM	Chen et al. (2003)	C/R/G	FV
GETM	Burchard and Bolding (2002)	C	FV

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MITgcm	Marshall et al. (1997)	C/R/G	FV
ROMS	Shchepetkin and McWilliams (2005)	R	FV
SCHISM	Zhang et al. (2016)	C/R/G	FV/FE
SELFE	Zhang and Baptista, 2008	C	FV/FE
SHYFEM	Umgiesser et al. (2004)	C	FE
SUNTANS	Fringer et al. (2006)	C	FV
TRIM/UnTRIM	Casulli (1999), Casulli and Zanolli (2002, 2005)	C	FV

3.3 Fine resolution nested models, downscaling and upscaling

High-resolution coastal services must properly resolve interactions between various coastal processes, including nearshore, estuarine, shelf, drying, and flooding dynamics. Achieving this requires a resolution of approximately 10-100 meters. Simultaneously, it is essential to capture open ocean processes at a resolution of around 1 kilometer or coarser. Common approaches employed in addressing this challenge include downscaling and multi-nesting techniques (e.g., Debreu et al., 2012; Kourafalou et al., 2015b; Trotta et al., 2017) as well as the use of unstructured-grid models (e.g., Zhang et al., 2016a, 2016b; Federico et al., 2017; Stanev et al., 2017; Ferrarin et al., 2018; Maicu et al., 2018). Another important aspect to consider is upscaling (Schulz-Stellenfleth and Stanev, 2016), which becomes relevant when addressing the two-way interaction between coastal and open-ocean systems.

Most coastal models are one-way nested, relying heavily on forcing data from larger-scale models as the coastal system is primarily influenced by the atmosphere, the hydrology and the open ocean. Enhancing the horizontal resolution of the North Sea operational model from 7 to 1.5 kilometers has shown improvements in off-shelf regions, but biases persist over the shelf area, indicating the need for further enhancements in surface forcing, vertical mixing, and light attenuation.

While the downscaling of information from coarser global or regional models to high-resolution coastal models is well-established, the reverse process of upscaling is more challenging and continues to be a subject of research. Two-way nested models allow assimilated information from coastal observations, typically not assimilated by larger-scale forecasting systems, to propagate beyond the coastal region while maintaining dynamic consistency. This upscaling capability has the potential to benefit regional models. Coastal observations have demonstrated their potential to improve boundary forcing or surface wind forcing in regional models.

The coupling of a coarse-resolution regional model with a fine-resolution coastal model using a two-way nesting approach has been studied in the context of the straits connecting the North and Baltic Seas. The intricate topography and narrow cross-sections of the straits result in the dominance of small-scale motions, which play a vital role in the exchange between the two seas and significantly influence Baltic Sea stratification. The two-way nesting method, developed by exchanging information between the child model in the straits and the parent model in the seas, incorporates elements of data assimilation and allows for different vertical discretizations in each model. The Adaptive Grid Refinement in FORTRAN (AGRIF), originally developed by Debreu et al. (2008; 2012), has found wide application as a library for seamless spatial and temporal refinement over rectangular regions in the NEMO modeling framework (https://forge.ipsl.jussieu.fr/nemo/wiki/WorkingGroups/AGRIF).

3.4 Unstructured-Grid Models for Cross-Scale Coastal Dynamics

The use of unstructured-grid models is crucial for cross-scale modeling and effectively addressing the interactions between estuaries and the open ocean. One key aspect is the accurate representation of freshwater transformation from rivers, which is often oversimplified in ocean models by specifying river runoff as a point source. Unstructured-grid models, with their ability to employ higher-order spatial discretizations, demonstrate good skill in capturing subtidal, tidal, and intermittent processes in coastal and estuarine environments, providing a more realistic representation of estuarine processes and improved interface with estuarine models.

Compared to curvilinear and Cartesian grids, unstructured grids excel in resolving complex bathymetric features without significant grid stretching. Since bathymetry plays a fundamental role in governing the dynamics of estuaries and the near coastal zone, unstructured grid models offer greater accuracy and computational efficiency in numerical forecasting. Their flexibility also enables more effective resolution of multiscale dynamic features. Fine spatial resolution in unstructured-grid models allows for the resolution of secondary (transversal) circulation in estuaries and straits, thereby improving mixing and enhancing the representation of long-channel changes in stratification, as demonstrated by Haid et al. (2020).

However, the construction of grids and ensuring reproducibility in unstructured-grid modeling still present challenges. Grid generation is not always fully automated, and subjective decisions are often made based on the specific research problem, applications, and intended services. The development of more objective grid construction methods and reproducibility standards is an ongoing concern in unstructured-grid modeling (Candy and Pietrzak, 2018).

3.5 Observing System Simulation Experiments, Observing System Experiments and Data Assimilation

Data assimilation in coastal regions presents challenges due to the presence of multiple scales and competing forcings from open boundaries, rivers, and the atmosphere, which are often imperfectly known (Moore and Martin, 2019). However, studies by Oke et al. (2002), Wilkin et al. (2005), Shulman and Paduan (2009), Stanev et al. (2015, 2016), and others have demonstrated the value of assimilating HF radar observations to improve the estimation of the coastal ocean state.

Observing System Simulation Experiments (OSSE) and Observing System Experiments (OSE) have the capability to incorporate diverse observing systems, including satellite-based observations, HF radars, buoys with low-cost sensors, autonomous vehicles, and more. These approaches, when coupled with an assimilative system, can provide guidance on optimizing the observing network (Oke and Sakov, 2012; Fujii et al., 2019). They can help identify gaps in existing coastal observing networks, assess operational failure scenarios, and evaluate the potential of future observation types. Pein et al. (2016) used an OSE-type approach to investigate the impact of salinity measurements in the Ems Estuary on the reconstruction of the salinity field, identifying observation locations that are more suitable for model-data synthesis. This type of analysis can contribute to the design and optimization of both existing and future observational arrays, especially in coastal regions where fine resolution is required.

4 Summary and outlook

The critical importance of high-resolution coastal modeling is demonstrated in addressing the complexities of dynamic coastal systems. Coastal areas are shaped by the interplay of mesoscale and submesoscale processes, strong tidal currents, atmospheric and hydrologic forcing, and significant anthropogenic pressures. Advanced techniques, including turbulence closure models for capturing vertical mixing and parameterizations of bottom roughness and vegetation drag for representing energy dissipation, are essential for accurately modeling these systems. The nonlinear interactions between tidal currents and wind waves emerge as a particularly influential factor, affecting ocean circulation and improving the accuracy of sea surface temperature predictions.

It is shown that the integration of high-resolution observational data, such as HF radar for surface currents and the SWOT satellite mission for sea surface topography, has the potential of substantially enhancing the resolution and reliability of coastal models. These data facilitate a detailed characterization of processes in transition zones spanning estuaries, nearshore areas, and the open ocean. Improved coupling between regional and local models has advanced the representation of boundary conditions and enabled simulations of small-scale dynamics, essential for capturing the complexity of the coastal continuum.

The application of data assimilation techniques addresses the rapid variability inherent in coastal processes, highlighting the challenges and limitations of predictability in these highly dynamic environments. Strategies to extend the accuracy of short-term and localized forecasts are provided, leveraging multiscale data integration to refine predictions. The ability to simulate interactions between atmospheric conditions, hydrological inputs, and oceanographic processes strengthens the foundation for more accurate modeling. This contribution underscores the importance of bridging observational and modeling gaps to achieve a comprehensive understanding of coastal systems. It highlights the necessity of integrating small-scale dynamics with broader processes to better inform sustainable coastal management practices. By aligning advanced techniques with high-resolution data, this work offers a pathway for more robust representations of coastal ocean dynamics and supports informed decision-making in the face of growing environmental and societal challenges.

Several directions for advancing coastal ocean modelling to address evolving environmental and societal challenges are highlighted. Future efforts should focus on integrating emerging observational technologies, such as high-resolution satellites (e.g., SWOT), autonomous platforms like gliders and drones, and hyperspectral imaging. These tools, combined with machine learning techniques for data analysis, can bridge gaps in spatial and temporal data coverage, providing a richer understanding of coastal dynamics.

Developing coupled modeling systems that seamlessly integrate atmospheric, hydrological, and oceanographic processes will be essential for capturing the complexities of the land-ocean continuum. Incorporating river runoff, estuarine dynamics, and nearshore processes into such systems will significantly enhance the scope and accuracy of predictions. Addressing

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computational challenges associated with high-resolution modeling is equally critical; this includes leveraging high-performance computing, cloud-based processing, and optimizing numerical schemes to achieve efficient and precise simulations.

Improving data assimilation techniques through ensemble approaches and probabilistic forecasting is another priority. These methods will better integrate multiscale observational data, reduce uncertainties, and enhance the reliability of predictions in dynamic environments. Concurrently, there is a pressing need to explore the impacts of climate change on coastal systems, including sea-level rise, increased storm intensity, and shifting precipitation patterns. Understanding these impacts will guide the development of adaptive strategies and strengthen resilience in vulnerable coastal zones.

The future of coastal modeling also depends on fostering interdisciplinary collaboration, engaging expertise from oceanography, meteorology, hydrology, and ecology. By aligning scientific research with societal needs and practical applications, collaborative frameworks can ensure the relevance and effectiveness of modeling efforts. Additionally, applying artificial intelligence to optimize model parameterization, grid design, and predictive analyses will unlock new capabilities for simulating small-scale processes like sediment transport and ecosystem responses.

Finally, enhancing global and regional coordination for coastal monitoring and modeling will be vital. Strengthening networks to ensure consistency in data and modeling approaches can foster international collaboration, facilitating the exchange of best practices and resources. These collective advancements promise to deepen our understanding of coastal systems and provide robust tools to manage and protect these critical areas sustainably in the face of ongoing and future challenges.

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Author contributions

JS conceptualized the study, analyzed data, and wrote this article. All authors contributed to the writing of the article and quality control.

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