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Review

The future of coastal and estuarine modeling: Findings from a workshop

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ABSTRACT

This paper summarizes the findings of a workshop convened in the United States in 2018 to discuss methods in coastal and estuarine modeling and to propose key areas of research and development needed to improve their accuracy and reliability. The focus of this paper is on physical processes, and we provide an overview of the current state-of-the-art based on presentations and discussions at the meeting, which revolved around the four primary themes of parameterizations, numerical methods, in-situ and remote-sensing measurements, and high-performance computing. A primary outcome of the workshop was agreement on the need to reduce subjectivity and improve reproducibility in modeling of physical processes in the coastal ocean. Reduction of subjectivity can be accomplished through development of standards for benchmarks, grid generation, and validation, and reproducibility can be improved through development of standards for input/output, coupling and model nesting, and reporting. Subjectivity can also be reduced through more engagement with the applied mathematics and computer science communities to develop methods for robust parameter estimation and uncertainty quantification. Such engagement could be encouraged through more collaboration between the forward and inverse modeling communities and integration of more applied math and computer science into oceanography curricula. Another outcome of the workshop was agreement on the need to develop high-resolution models that scale on advanced HPC systems to resolve, rather than parameterize, processes with horizontal scales that range between the depth and the internal Rossby deformation scale. Unsurprisingly, more research is needed on parameterizations of processes at scales smaller than the depth, including parameterizations for drag (including bottom roughness, bedforms, vegetation and corals), wave breaking, and air–sea interactions under strong wind conditions. Other topics that require significantly more work to better parameterize include nearshore wave modeling, sediment transport modeling, and morphodynamics. Finally, it was agreed that coastal models should be considered as key infrastructure needed to support research, just like laboratory facilities, field instrumentation, and research vessels. This will require a shift in the way proposals related to coastal ocean modeling are reviewed and funded.

Contents

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1. Introduction

Coastal and estuarine modeling is concerned with understanding and predicting marine processes in coastal oceans and estuaries. Although this includes physical and biogeochemical processes, the focus of this paper is on the physical processes impacted by tides, winds, surface waves, and hydrological processes including fresh water and sediment-laden flows. One component of coastal and estuarine modeling is the prediction of sediment transport, including both fine sediments in shallow estuaries and coarser sediments in nearshore, wave-driven environments. Over long time scales, sediment transport governs morphodynamics which strongly impacts coastal and estuarine flows. Unique to coastal and estuarine modeling is the connection to human influences particularly in densely populated coastal regions, where flows can be altered by coastal structures, dredging and sand nourishment operations, and anthropogenic sources of contaminants and nutrients significantly impact coastal biogeochemistry. Given that roughly 60% the world's population lives within 60 km of the coast and this is expected to rise to 75% within a few decades (Rao et al., 2008), accurate coastal and estuarine modeling is an essential component of efficient management for the sustainability of natural coastal systems and the development and improvement of sustainable urban infrastructure, particularly in the face of rapid urbanization of coastal cities and changing climate including sea-level rise. Accurate coastal and estuarine modeling is also a critical component of climate modeling because coastal shelves contain roughly the same amount of primary productivity and biomass as the open ocean (Whittle, 1997; Sharp, 1988; Yool and Fasham, 2001).

The focus on physical processes in this paper rests on the assumption that they are fundamental to modeling nearly all other processes in the coastal ocean, including pollution transport, water quality, biogeochemistry and coastal ecology, since modeling each of these requires coupling to a circulation model that computes the transport and mixing. In the context of modeling of physical processes, in this paper we will distinguish between two distinct types of ocean modeling. At larger, or regional scales, regional ocean models typically assume a geostrophic balance to leading order (i.e. rotation in balance with pressure gradients) and are weakly dissipative. At smaller coastal and estuarine scales, coastal models are fundamentally ageostrophic, three-dimensional, and driven by boundary-layer processes. In the shallowest regions of the coastal environment, coastal models must accurately capture frictional balances, such as between the barotropic or baroclinic pressure gradients and bottom friction. When simulating strong tides or storm surges, coastal models must also account for wetting and drying and hydrological forcing to account for the effects of runoff from precipitation. Coastal models meant to capture the transitional nature between shallow environments and regional scales must be able to simulate both highly frictional, ageostrophic motions and balanced flows.

Models of physical processes in coastal environments have seen significant advances in the past two decades owing to increases in computational power and improved numerical methods including unstructured grids, model nesting, data assimilation, and model coupling. Furthermore, advances in remote-sensing and in-situ observational technologies have led to substantially larger and more accurate datasets, which have significantly improved the ability to assess model performance. Multiple coastal models have been developed in the past two decades, although there is no dominant model, in sharp contrast to regional modeling, for which the ROMS model (Shchepetkin and McWilliams, 2005) is the most common in the United States, or wave modeling, for which the SWAN model (Booij et al., 1999) is the most common for coastal wave problems in the United States. As an example, while few, if any models other than ROMS have been used to simulate regional circulation on the U.S. West Coast (e.g. Neveu et al., 2016; Chao et al., 2009, 2018), circulation in San Francisco Bay has been modeled with at least six different models in the past ten years: (1) SUNTANS (Fringer et al., 2006) was applied by Chua and Fringer (2011) and Holleman et al. (2013), (2) UnTRIM (Casulli and Zanolli, 2002, 2005) was applied by MacWilliams et al. (2015, 2016), (3) TRIM3D (Casulli and Cattani, 1994) was applied by Gross et al. (2009), (4) SCHISM (Zhang et al., 2016) was applied by Chao et al. (2017b), and (5) Delft3D-Flow and (6) Delft3D-FM (oss.deltares.nl/web/deflt3d/home) were applied by Erikson et al. (2013) and Martyr-Koller et al. (2017), respectively. Although there have been no systematic comparisons of these models, the most detailed calibration and best performing model appears to be the UnTRIM implementation by MacWilliams et al. (2015, 2016), although it is difficult to argue that the performance can be attributed to the model itself as opposed to superior grids, bathymetry, and forcing (i.e. winds, tides, river inflows, etc…).

The fact that there is no dominant coastal ocean modeling strategy like that seen in regional modeling presents an opportunity to determine whether there is a need for a unified approach in coastal ocean modeling. Obviously, there is no need for such an approach if existing strategies are efficient and accurate enough to answer pressing questions related to coastal processes. To this end, a workshop was held to determine the current state-of-the-art in coastal ocean modeling and to form a consensus on key areas of research and development needed to improve the accuracy and reliability of such models. Key questions posed to workshop participants and that will be addressed in this paper are:

(1) Where should we focus our efforts related to improved parameterizations in coastal modeling?
(2) What aspects of numerical methods related to coastal modeling can be improved?
(3) How can in-situ and remote-sensing measurements be used, and improved, to benefit coastal modeling?
(4) How can coastal modeling better leverage HPC resources?

There have been other recent workshops with similar objectives. The paper by Wilkin et al. (2017) summarizes the outcomes of an IOOS-sponsored workshop that was held to "advance coastal ocean modelling, analysis and prediction as a complement to the observing and data management activities of the coastal components of the U.S. Integrated Ocean Observing System (IOOS) and the U.S. Global Ocean Observing System (GOOS)". The findings of that workshop concluded that the community should focus on the following seven topical areas:

(1) Model coupling
(2) Data assimilation
(3) Nearshore processes
(4) Cyberinfrastructure and model skill assessment
(5) Modeling for observing system design and operation
(6) Probabilistic prediction methods
(7) Fast predictors

As will be discussed below, the findings of the workshop discussed in this paper are similar, although the recommendations focus more on process and forward modeling rather than predictive and data assimilative modeling for observing systems like IOOS and GOOS. There are also coastal modeling initiatives in Europe with similar objectives, such as the German coastal modeling working group[1] that is charged with "Defining challenges for coastal modeling, encouraging cooperation between developers and users, developing a national forum for coastal ocean modelling, and developing common infrastructure". As part of that working group, a workshop was held in Germany[2] in February 2018 with the goal of "increasing the communication between coastal ocean modellers in German marine research institutions" and focused on answering the following questions:

(1) What are the future challenges in coastal ocean modeling?
(2) Do we need better coordination between model developers and model applicants on the national level?
(3) Could we profit from a common repository of reference model results?
(4) Would we profit from a coastal ocean model intercomparison study (CoastalMIP)?
(5) Do we need to develop new models or are we happy with what we have?
(6) Do we need common interfaces for model and module coupling?
(7) Are the national (super)computing resources sufficient?

[1] http://www.deutsche-meeresforschung.de/en/coastalmodelling
[2] https://www.io-warnemuende.de/comod2018.html

Rather than providing a comprehensive review of the state-of-the-art in modeling of physical processes in the coastal ocean, this paper summarizes key issues as presented and discussed by workshop attendees. These issues range from numerical methods to parameterizations to observational technologies. For a comprehensive overview of numerical methods for coastal models, the reader should consult the review article by Klingbeil et al. (2018). Klingbeil presents details of time discretization and wetting and drying schemes, topics not mentioned in this report but that are crucial to coastal ocean modeling. The reader should refer to the review article by Medeiros and Hagen (2013) or the paper by Candy (2017) for a detailed discussion of wetting and drying algorithms. In addition to a discussion of wetting and drying, no overview of ocean modeling would be complete without a discussion of the state-of-the-art in Lagrangian particle tracking, a review of which is given by van Sebille et al. (2018). Although nearshore wave and sediment transport modeling were discussed at the workshop and in this report, a more detailed review can be found in Kirby (2017).

2. Workshop organization and attendees

A four-day workshop, funded by the U.S. National Science Foundation (NSF) Physical Oceanography Program, was held during June 18–21, 2018 at the Stateview Hotel and Conference Center in Raleigh, NC, U.S.A., on the campus of North Carolina State University. A total of 40 participants attended the workshop, 29 of whom were more senior and gave 15 min presentations (See Appendix). The senior researchers nominated 11 junior scientists who were allotted 30 min for their presentations. Research interests among the participants reflected a balance between model developers and users. Among the developers and users, interests were equally divided between those with a stronger coastal focus and those with a stronger estuarine focus. Roughly half of those focusing on coastal processes had interests in storm surge modeling, while six researchers had specific interests in coastal engineering and/or nearshore processes. Finally, there were three biogeochemists and two researchers focusing on wetlands. Most of the attendees were forward or process modelers, and hence the outcomes focused less on data assimilation techniques more commonly employed in operational modeling. Indeed, an important outcome of the workshop is the need for greater collaboration between forward and operational modelers and for forward modelers to adopt more techniques commonly employed in the operational and predictive modeling communities.

Many of the original developers of most of the popular coastal models used in the United States were present at the meeting (see Table 1), including the finite-element ADCIRC model (Luettich et al., 1992; Westerink et al., 1994), the ROMS-based, Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System, COAWST (Warner et al., 2008, 2010)), the finite-volume, unstructured-grid model FVCOM (Chen et al., 2003), the curvilinear-coordinate, finite-volume model GETM (Burchard and Bolding, 2002), the general ocean turbulence modeling framework GOTM (Burchard et al., 1999), the mixed finite-element/finite-volume models SELFE (Zhang and Baptista, 2008) and SCHISM (Zhang et al., 2016), and the finite-volume, unstructured-grid and nonhydrostatic SUNTANS model (Fringer et al., 2006). Also present was the developer of the biogeochemical model COSINE (Chai et al., 2002, 2003, 2007). Other popular models are also discussed in this paper, as listed in Table 1.

3. State of the art

3.1. Parameterizations

3.1.1. The coastal submesoscale and turbulence modeling

Unresolved processes that must be parameterized in coastal modeling can be regarded as those that are smaller than the "estuarine submesoscale" or "coastal submesoscale" (Geyer, this workshop), in analogy to ocean submesoscale processes in regional or global ocean modeling. Like the ocean submesoscale, coastal submesoscale processes can be thought of as those with horizontal scales that are smaller than the internal Rossby deformation scale. However, unlike ocean submesoscale processes, submesoscale coastal processes are constrained by bathymetric and coastline scales which are typically smaller than the Rossby deformation scale. Therefore, coastal submesoscale processes possess horizontal scales that are larger than the depth but smaller than the relevant horizontal bathymetric scale. As a result, they depend heavily on coastline geometry, and might include processes like lateral/vertical flow separation, headland eddies, secondary flows, and fronts (for an example of the importance of bathymetry in coastal and estuarine processes, see Ye et al., 2018). Unlike regional scales for which there is active research on parameterization of submesoscale processes (e.g. Pearson et al., 2017; McWilliams, 2016; Thomas et al., 2013), there has been little work on parameterizing such processes in coastal models because they are so site specific. Instead, efforts have focused on resolving these processes with high resolution. For example, Giddings et al. (2012) showed that the SUNTANS model could resolve, using O(1 m) horizontal resolution, a front at a convergence zone between two tidal channels in the Snohomish River Estuary that was measured in-situ and with remote sensing. Giddings (this workshop) showed that coupled ROMS-SWAN model results accurately capture frontal behavior of a small river plume front interacting with the surf zone at the mouth of the Tijuana River Estuary. This model employed five nested ROMS model grids, ranging from the regional scale down to the surf zone with a resolution of O(10 m) on the finest grid. These examples demonstrate the need for extremely high resolution to resolve, rather than parameterize, so-called coastal submesoscale processes.

While parameterization of coastal submesoscale processes is difficult if not impossible, there are many parameterizations of small-scale processes in coastal models with scales that are on the order of the depth (i.e. either the bottom or the mixed-layer depth) or smaller, including turbulence. Coastal models compute the low-frequency, large-scale motions dictated by the Reynolds-Averaged Navier–Stokes (RANS) equations (along with the hydrostatic approximation; See Section 3.2.9). Typically, turbulence models focus on the vertical turbulent Reynolds stress arising from the averaging. Horizontal Reynolds stresses are typically ignored in coastal models given the dominance of horizontal transport compared to horizontal turbulent mixing in most problems of interest (e.g. Blumberg and Mellor, 1987). The remaining vertical turbulent Reynolds stress is modeled with a turbulent-viscosity hypothesis which assumes the Reynolds stress is a product of a turbulent eddy-viscosity and the mean vertical shear (Pope, 2000). Most parameterizations of the turbulent eddy-viscosity in coastal modeling assume that it is a product of turbulent length and velocity scales that are inferred from two-equation turbulence closure schemes (for a review, see Umlauf and Burchard (2005)). The first of these equations is an evolution equation for the turbulent kinetic energy (TKE), from which the turbulent velocity scale can be extracted, and the second equation is needed to compute the turbulent length scale. Examples include the Mellor–Yamada level 2.5 scheme (Mellor and Yamada, 1982), the k-epsilon model (Jones and Launder, 1972; Launder and Sharma, 1974; Rodi, 1984), and the k-omega model originally proposed by Saffman (1970) and extended to oceanic applications by Umlauf et al. (2003). Although these models have similar TKE equations, they differ in the implementation of the length-scale related equation. Umlauf and Burchard (2003) show that this second equation can be generalized as a generic length scale (GLS) model that exhibits more flexibility than the traditional models in that it performs well when applied to a much broader variety of problems. The GLS model is written in a form that recovers the traditional models through alteration of the parameters in the governing equation for the generic length scale, making it straightforward to compare all commonly used two-equation models. The GLS approach was incorporated into the ROMS model (Warner et al., 2005) and in the General Ocean Turbulence Model, GOTM (Burchard et al., 1999; gotm.net), the standard platform for turbulence parameterizations in coastal modeling.

A fundamental difficulty related to turbulence modeling for coastal problems concerns the relationship between stratification and turbulence (see the review by Umlauf and Burchard, 2005). Although parameterization of stratified turbulent mixing remains an active area of research (e.g. Gregg et al., 2018; Monismith et al., 2018), most coastal models produce reasonable results with stability functions that damp the turbulence due to stratification. In this approach, a critical or steady-state Richardson number is specified below which turbulence grows exponentially and above which turbulence decays exponentially (Burchard and Baumert, 1995). Theory (Miles, 1961; Howard, 1961) and experiments (Rohr et al., 1988) have found the steady-state Richardson number to be around 0.25. A lower steady-state Richardson number requires stronger shear to incur vertical mixing, and hence will produce a more strongly-stratified environment. Although the steady-state Richardson number is predicted from theory, it can be tuned to account for modeling errors like numerical mixing, as discussed in Section 3.2.5.

3.1.2. Bottom drag

Other than the turbulence model, the most common parameterization of small-scale processes in coastal models is that related to bottom drag. Most models compute a bottom stress that is dictated by a prescribed bottom roughness and the assumption that the horizontal velocity in the first grid cell above the bed satisfies a logarithmic velocity profile. Although this assumes that the bottom-most cell is within the log-law region, in practice it is often relaxed, most notably when calculating the drag coefficient for two-dimensional, depth-averaged models which assume a log-law throughout the water column. As an example, the drag coefficient for the external or barotropic mode in GETM assumes a log-law velocity profile at mid-depth (Burchard and Bolding, 2002). The bottom roughness can be parameterized as a function of the grain size distribution and, less commonly, the presence of bedforms. While bottom drag in steady, flat, rough boundary layers can be accurately parameterized if the median grain size is known, there are few parameterizations for the bottom roughness in the presence of bedforms, the most common being the wave-dominated parameterization of Wiberg and Harris (1994) that is implemented in the wave, current, and sediment-transport component (described in Warner et al., 2008) of the COAWST model. There are few, if any, coastal models that employ parameterizations for bedforms in steady flows, although there is evidence that the bottom drag coefficient depends on the tidal phase owing to bedform asymmetry (Fong et al., 2009). Bottom roughness parameterizations in wave models are similar to those in circulation models, in that the wave friction factor is a function of the properties of the bed. However, wave models include dissipation by wave breaking and bottom dissipation due to viscous damping in mud which absorbs wave energy (e.g. Komen et al., 1994). Such models are highly uncertain given the difficulty in predicting the behavior of bottom mud layers in coastal regions.

Models for the bottom drag that include the combined effects of currents and surface waves employ more complicated parameterizations like the theory of Grant and Madsen (1979), which parameterizes wave effects with an augmented roughness, or Mellor (2002), in which the waves are accounted for with an augmented shear production. The augmented roughness of Grant and Madsen (1979) is typically further modified based on the effects of sediment-induced stratification, which acts to reduce near-bed turbulence and the effective bottom

Table 1
Models mentioned in this paper, in alphabetical order by model name. In the grid/variable placement column, B and C refer to the grid types of Arakawa and Lamb (1977).

Model	Citation	C: Coastal, R: Regional, G: Global	Finite-volume (FV) or Finite-element (FE)	Grid/variable placement	Vertical coordinate	Developer (s) present?	Notes/unique features
ADCIRC	Luettich et al. (1992) Westerink et al. (1994)	C	FE		Sigma	Blaine, Luettich, Westerink	Continuous/Discontinuous Galerkin
COAWST	Warner et al. (2008, 2010)	C/R	FV	C	Sigma	Signell, He, Ganju	Coupled Atmosphere/wave/sediment
COSINE	Chai et al. (2002, 2003, 2007)	C/R	–	–	–	Chai	Biogeochemical model
Delft3D-Flow/Delft3D-FM	oss.deltares.nl/web/delft3d/home	C	FV	C	Sigma	No	
ECOM-si/POM	Blumberg and Mellor (1987)	C/R	FV	C	Sigma	No	
FunwaveC	Feddersen et al. (2011)	C	FV	C	2D (x-y)	Kirby, Shi	2D Boussinesq wave model
FVCOM	Chen et al. (2003)	C/R/G	FV	B	Sigma	Chen	
GETM	Burchard and Bolding (2002)	C	FV	C	Sigma/Adaptive	Burchard	Numerical mixing analysis
GOTM	Burchard et al. (1999)	C	–	–	1D (Z)	Burchard	Turbulence Model
HYCOM	Bleck and Boudra (1981)	R/G	FV	C	Sigma/Z/Isopycnal	No	Hybrid/Isopycnal coordinates
MARS3D	Lazure and Dumas (2008)	C/R	FV	C	Sigma	No	
MITgcm	Marshall et al. (1997a)	C/R/G	FV	C	Z	No	Shaved cells
NHWAVE	Ma et al. (2012) Shi et al. (2015)	C	FV	C	Sigma	Kirby, Shi	Nonhydrostatic 3D wave model, LES
ROMS	Shchepetkin and McWilliams (2005)	R	FV	C	Sigma	Wilkin	
SCHISM	Zhang et al. (2016)	C/R	FV/FE	C/FE	Z/Sigma	Zhang	Locally-adaptive vertical coordinate
SELFE	Zhang and Baptista (2008)	C	FV/FE	C	Z/Sigma	Zhang, Baptista	
SLIM	Vallaeys et al. (2018)	C/R	FE		Z/Sigma/ Adaptive	No	Discontinuous Galerkin
SUNTANS	Fringer et al. (2006)	C	FV	C	Z	Fringer	
SWAN	Booij et al. (1999)	C/R	FV	C	2D (x-y)	No	Phase-averaged wave model
SWASH	Zijlema et al. (2011)	C	FV	C	Sigma	No	2D/3D Boussinesq wave model
TRIM/UnTRIM	Casulli (1999), Casulli and Zanolli (2002, 2005)	C	FV	C	Z	No	Subgrid bathymetry
WaveWatch III	Tolman (2009)	R/G	FV	C	2D (x-y)	No	Phase-averaged wave model
WRF-Hydro	Gochis et al. (2018)	C/R	–	–	–	No	Atmospheric/hydrological model

drag (e.g. Glenn and Grant, 1987; Styles and Glenn, 2000). Much work on bottom drag has been done with large-eddy simulation (LES) and direct-numerical simulation (DNS), with a focus on understanding sediment transport which is highly sensitive to the bottom drag parameterization. Examples include steady-current simulations (Cantero et al., 2009a,b) and purely wave-driven simulations (Ozdemir et al., 2010; Yu et al., 2013; Cheng et al., 2015), although there is little LES or DNS work on wave–current flows. Parameterizations accounting for waves typically augment the mean bottom stress or roughness under the assumption of turbulent wave boundary layers over rough beds. While this is common in coastal nearshore environments, in estuaries where waves are generally weaker, laminar wave boundary layers are possible and can reduce the mean or effective roughness (Nelson and Fringer, 2018).

3.1.3. Vegetation, kelp, and coral drag

Bottom drag parameterizations for coastal modeling are often of second-order importance when compared to the need for accurate boundary conditions and forcing (See Section 3.2.3), and in many cases the bottom drag is heavily tuned (See Section 3.2.5). Drag parameterizations can be more important where the impact of larger-scale roughness features on flow and waves is significant, such as vegetation, kelp, or corals. A recent example of the state-of-the-art in parameterizing vegetation drag is the coupled ROMS-SWAN, flow-wave-vegetation model of Beudin et al. (2017) implemented in the COAWST model. The vegetation model includes three-dimensional vegetation drag that extracts momentum from the flow in the region of the water column that is influenced by vegetation through a quadratic drag law (Nepf, 2012). This drag decelerates the flow that is blocked by vegetation while accelerating it above submerged vegetation, which in turn acts to locally decrease the effective water column depth. The shear layer that develops at the interface between the submerged vegetation and the flow contributes to turbulence and is added as a production term to the TKE equation in the GOTM model, following the approach of Uittenbogaard (2003). At the same time, fine-scale eddies generated by separated flow around vegetation stems extract kinetic energy from the turbulence, a process that is modeled with a dissipation term in the TKE equation. In a similar vein, vegetation acts to damp waves with an energy dissipation term in the wave-action equation in the SWAN model, following the method described by Mendez and Losada (2004). The model of Beudin et al. (2017) also includes the effect of wave streaming observed by Luhar et al. (2010) and Luhar and Nepf (2013), in which a force is added to the horizontal momentum equations in the ROMS model to account for the contribution of wave-induced mean flow within the vegetation, like streaming in the wave boundary layer without vegetation. Further complicating the dynamics is the bending of submerged vegetation such as seagrass, which leads to a reduction in the drag coefficient with increased flow strength, an effect that is described by Luhar and Nepf (2011). Such complexities are accentuated when parameterizing drag coefficients for flow through kelp, for which the drag coefficient varies with the tidal cycle and seasonal changes in kelp density (Rosman et al., 2010; Wang et al., 2018). Coral reefs represent an added modeling challenge given the dominance of waves and wave breaking in those environments (Monismith, 2007). Models of circulation in coral reef environments can incorporate detailed spatial variability of the effective roughness derived from remote sensing and in-situ measurements, such as the COAWST model of the Palmyra Atoll by Rogers et al. (2017).

Ultimately, although there are numerous parameterizations for vegetation, kelp, and coral reef effects, most parameterizations are based on idealized laboratory experiments with the drag elements represented by simplified arrays of rigid columns (e.g. Lowe et al., 2005a,b), model seagrass blades (e.g. Zeller et al., 2014) or model kelp (Rosman et al., 2013). Some studies focus on flow around the skeletal structure of real coral experimentally (e.g. Reidenbach et al., 2006) or numerically (e.g. Chang et al., 2014). Nevertheless, there are no parameterizations that account for the spatially heterogeneous nature of real vegetation, kelp, or corals, such as cross-sectional geometry, drag coefficient, density, height, area density, Young's modulus, etc… Although such parameterizations are badly needed, the primary difficulty of implementing them in coastal models is related to accurately measuring the distribution of such properties in the field.

3.1.4. Sediment transport modeling

Like modeling vegetation-induced impacts, sediment transport modeling is limited in large part by a lack of knowledge of the spatio-temporal distribution of sediment properties in coastal environments. Examples of the current state-of-the-art in sediment transport modeling for coastal problems can be found in the Delft3D-Flow/Delft3D-FM (oss.deltares.nl/web/deflt3d/home) and COAWST (Warner et al., 2008) models. In these models, it is assumed that the suspended sediment can be treated as an Eulerian concentration field because the grain sizes and flow regimes ensure that the sediment grains effectively follow the flow (i.e. they possess a small Stokes number, which is a ratio of the particle relaxation time scale to the fine-scale turbulent shearing time scale) and the concentration is small enough (less than roughly 1 g L^{-1}) to ignore interactions between sediment grains (Balachandar and Eaton, 2010). This allows coastal models to use existing momentum and/or scalar transport schemes to transport sediment, with the addition of a term to account for gravitational settling. To represent transport of a particle size distribution (PSD), most models transport three or more size classes, each with the theoretical settling velocity for that grain size. Examples of models with multiple size-class distributions are the Mekong River two-size class sediment transport study of Xue et al. (2012) using COAWST, the Skagit River tidal flats three-dimensional model of Ralston et al. (2013), which employed three size classes (fine sand, silt, and fine silt) using FVCOM, the San Francisco Bay sediment transport model of Bever and MacWilliams (2013) using UnTRIM, which accounted for four size classes (silt, flocculated clay and silt, sand, and gravel), and the Seine Estuary sediment transport model of Grasso et al. (2018) using MARS3D (Lazure and Dumas, 2008), which accounted for five size classes (gravel, 3 sand sizes, and one mud size class). The choice of a limited number of size classes implies a coarse representation of the actual PSDs. Therefore, the settling velocities are based on representative grain sizes and are largely tunable.

The settling velocity is particularly important in estuarine environments which possess fine-grained sediments (silts and clays) with the propensity to flocculate, or aggregate, due to cohesive forces arising from salinity or biological effects. Flocculation is, in turn, countered by breakup in the presence of turbulent shear, implying that the PSD cannot be specified a-priori because it evolves in time. The most common approach to account for these effects is to parameterize the average settling velocity as a function of the flow, sediment, and turbulence properties, as reviewed by Soulsby et al. (2013). As examples, Mengual et al. (2017) and Grasso et al. (2018) used the MARS3D hydrodynamic model (Lazure and Dumas, 2008) and parameterized the settling velocity as a function of the suspended sediment concentration (SSC) and turbulent shear rate using the formula of Van Leussen (1994). The next level of complexity is to explicitly simulate the evolution of the average floc diameter through parameterizations that account for the effects of concentration and turbulent shear on the flocculation and breakup processes (e.g. Winterwerp et al., 2006). The average settling velocity is then computed with knowledge of the average floc diameter and assumptions about the floc density using fractal theory. The disadvantage of this approach is that it does not account for the existence of a PSD and its variation in time due to flocculation and breakup. This can be accounted for by exchanging mass between different size classes, or flocs, with the population balance approach (Lick et al., 1992; Sterling et al., 2005), wherein smaller size classes can interact, flocculate, and lose mass to larger size classes, and larger size classes can lose mass to smaller size classes through turbulent breakup. The primary advantage of the population balance approach is that it is based on first principles, although it requires numerous parameterizations with many coefficients to model the aggregation and breakup interaction dynamics between the different size classes. A good example is the FLOCMOD model of Verney et al. (2011) that was incorporated into COAWST by Sherwood et al. (2018). Although this model shows great promise, population balance models remain in their infancy owing to the need for extensive calibration of the many unknown parameters. In addition to the difficulty of modeling the physical processes, flocculation also depends critically on biological material in the water column which can promote aggregation (Kranck and Milligan, 1980; Mietta et al., 2009). However, no coastal models explicitly couple biological models to sediment transport models to account for this. Interestingly, such coupling is inherently two-way given that the biology is modified by light availability which is a strong function of the SSC (Cloern, 1987). Because of the difficulty in parameterizing flocculation, some coastal models ignore flocculation parameterizations and assume static floc sizes with behavior that is essentially tuned to match observations. For example, Chou et al. (2018) showed that the SSC in South San Francisco Bay could be reproduced reasonably well with a sediment transport model in SUNTANS after tuning the relative erosion rates of two size classes which were referred to as "microflocs" and "macroflocs".

An additional complication of sediment transport modeling is the erosion of sediment from the bed, which is typically parameterized empirically with a power law as a function of the ratio of the bottom stress, τ_b, to the critical bottom stress below which no erosion is expected to occur, τ_c. Sanford and Maa (2001) pointed out that there are many variants of these empirical expressions and all appear to behave similarly. In practice, the most common form is $\mathrm{E} = M(\tau_b/\tau_c - 1)^n$ (Winterwerp and van Kesteren, 2004), where models focusing on cohesive sediments set $n = 1$ (e.g Warner et al., 2008; Bever and MacWilliams, 2013; Chou et al., 2018) and models incorporating both cohesive and non-cohesive sediments use $n = 1$ for the cohesive sediments and $n = 1.5$ for the non-cohesive sediments or sands (e.g. Mengual et al., 2017; van Kessel et al., 2011). Delft3D-Flow (2019) uses the erosion formula with $n = 1$ for cohesive sediments and a reference concentration approach (van Rijn, 1993) for erosion of non-cohesives. The bottom stress τ_b is typically obtained with parameterizations based on the bottom roughness and wave properties, with the additional complication that the near-bed sediment-induced stratification can reduce the bottom stress (see Section 3.1.2). The variability with depth in the bed is accounted for by incorporating multiple sediment layers with varying critical stresses (τ_c) erosion rates (M), and other sediment properties, such as mud and sand/mud mixtures (e.g. Warner et al., 2008; Sherwood et al., 2018; Delft3D-Flow, 2019). It is often the case that just two layers are sufficient to account for the existence of an easily erodible top "fluff" layer (Lick, 2009) composed of fine, muddy sediments, and a more consolidated sandy lower layer that is less erodible (e.g. van Kessel et al., 2011). Delft3D-Flow (2019) has a separate mud module that computes the momentum conservation equations in the mud layer, and mass conservation is governed by the horizontal transport of mud, consolidation, and entrainment and deposition to/from the flow. The critical stresses for erosion (τ_c) and the erosion rates (M) are often obtained from core samples in laboratory settings such as Sedflume

(McNeil et al., 1996). Erosion rates and critical shear stresses respectively decrease and increase with time owing to consolidation of the bed in fine-grained, muddy environments. These effects that can be accounted for with empirical approaches, such as the model of Sanford (2008) that was incorporated into COAWST (Sherwood et al., 2018).

While suspended sediment transport modeling has its limitations, accurate bed-load transport modeling is even more limited by inaccurate parameterizations and a lack of knowledge of bed properties, particularly in fine-grained or muddy estuarine environments. Bed load is better defined in sandy environments because movement of sand grains under steady flow can be parameterized with models like the Meyer-Peter and Müeller formula (1948), wherein the bed-load transport rate is given by a power law as a function of τ_b/τ_c, much like the parameterization for erosion. The formula by Soulsby and Damgaard (2005) computes the time-averaged bed-load transport in sandy beds due to wave–current flows and accounts for misalignment between waves and currents. These bed-load transport formulas require calculation of bottom stresses due to wave–current flows, as described in Section 3.1.2. Several parameterizations account for modifications in bed-load transport due to bed slope. The critical stress for erosion can be increased with increasing slope to effectively decrease the bed-load transport in the upslope direction (Whitehouse and Hardisty, 1988). Alternatively, the bed-load transport can be directly modified as a function of the bed slope to yield similar behavior (Lesser et al., 2004).

Morphodynamic evolution of the bed is dictated by both suspended and bed-load transport through the Exner sediment mass balance equation, in which the bed height evolves due to deposition and erosion of suspended load transport and divergence of the bed-load transport. Implementations of the Exner equation require a smoothing or diffusion term which is typically derived with the avalanching approach, for which a bed-load flux causes a decrease in bed slope if it exceeds the local angle of repose (e.g. Chou and Fringer, 2010; Guerin et al., 2016). Without this term, grid-scale oscillations appear in the bed height given that the Exner equation otherwise has no mechanism to smooth out such oscillations. The most difficult aspect of morphodynamics modeling is that the bed evolves over time scales that are much longer than typical time scales in coastal models. Therefore, to reduce the computational cost associated with the hydrodynamics, most morphodynamics studies are run in two dimensions with depth-averaged models (e.g. van der Wegen and Roelvink, 2008). While computationally less expensive, two-dimensional models do not capture subtidal estuarine dynamics which are largely baroclinically driven. Only recently have three-dimensional morphodynamics studies been implemented to assess the role of density-driven currents (Olabarrieta et al., 2018). To study long-term morphodynamics over decades or even centuries, it is common to employ a morphological scale factor (Roelvink, 2006), in which the bed evolution is multiplied by a factor during each time step to accelerate its motion relative to that of the flow (Olabarrieta et al. used a factor of 50; van der Wegen and Roelvink used 400). Owing to the potential for extensive erosion over long morphological time scales, an added difficulty of long-term morphological modeling is its dependence on sediment properties deep within the bed. While these can be measured with core samples, core sampling can be extremely expensive and may not provide adequate horizontal spatial resolution. A more extensive discussion of different bed-load transport and morphodynamics models can be found in the user manual for the Delft3D family of models (Delft3D-Flow, 2019).

3.1.5. Wave modeling

A full description of the state-of-the-art and recommendations for future research in wave and nearshore modeling would warrant a workshop in and of itself. Therefore, here we discuss features of wave modeling that are most relevant for larger-scale (i.e. larger than nearshore scales) coastal circulation modeling in the context of coupling of wave models to three-dimensional circulation models. A review of nearshore wave modeling is provided by Kirby (2017).

Surface gravity wave time and length scales are too small to resolve in coastal models. Instead, the waves are modeled with the conservation of wave action equation which governs the evolution of the wave energy spectrum due to wind input, wave–wave interactions, and breaking. These models can accurately capture refraction by bathymetry and currents, although diffraction is extremely difficult to capture and hence associated parameterizations are not very reliable. Most coastal models include the effects of waves using the wave action approach, the most popular being WaveWatch III (Tolman, 2009) and SWAN (Booij et al., 1999), which are coupled to currents in the COAWST and Delft3D-Flow/Delft3D-FM models. Models with their own approaches to solving the wave action equation are similar to the SWAN approach such as the unstructured-grid wave models in FVCOM (Qi et al., 2009), SUNTANS (Chou et al., 2015), or SCHISM (Roland et al., 2012). Solution of the wave action equation is computationally costly given that the directional spectrum is typically resolved with roughly 30 angles and 30 frequencies, thus incurring O(1000) additional two-dimensional transport equations to compute transport of wave action by the group velocity and currents. In many cases, because the wave spectrum can evolve more slowly than the currents, this computational cost can be reduced by computing the waves less often than the currents.

There are two approaches to coupling the time-averaged effect of waves to the currents. The first is the radiation stress formalism, in which the waves drive currents with the divergence of the excess wave momentum flux, and has been the most common approach (e.g. Warner et al., 2008, 2010; Kumar et al., 2011). The second and recently more popular approach is the vortex force formalism in which the advective term in the horizontal momentum equations is written in terms of the divergence of the kinetic energy and a vortex force (McWilliams et al., 2004; Bennis et al., 2011) and has been implemented in the structured-grid ROMS (Uchiyama et al., 2010) and COAWST (Kumar et al., 2012) models and the unstructured-grid SCHISM model (Guerin et al., 2018). This approach has the advantage that it naturally decomposes the wave force into conservative and non-conservative parts which gives better results in the presence of wave breaking, particularly in the nearshore.

Of the many active areas of research in wave modeling, parameterizing the effects of transient rip currents by nearshore wave breaking is an important component of coastal modeling. Such currents are critical to accurately representing cross-shore transport past the breaker zone, an important mechanism for transport of tracers from small-discharge streams (Giddings, this workshop). Rip currents are not resolved in coastal models because wave models do not resolve the vertical vorticity arising from finite-crest-length breaking. To incorporate these effects into ROMS in the COAWST model, Kumar and Feddersen (2016, 2017) directly computed the vertical vorticity with the FunwaveC model (Feddersen et al., 2011), a two-dimensional Boussinesq wave model that resolves finite-crest-length breaking. The resulting vertical vorticity can be directly computed in FunwaveC and added as a source term to the ROMS model, which then produces transient rip currents. While this approach is costly because it requires computation of waves with FunwaveC, the ultimate objective is to develop parameterizations for these effects that can be incorporated into the circulation model at a fraction of the computational cost.

Coupling of winds and waves is a critical component of coastal wave modeling. Under weak to moderate wind settings, wave models can accurately reproduce wind-wave generation given the relatively accurate parameterizations of equilibrium and depth- or fetch-limited wave spectra. However, accurate wave modeling is elusive under extreme conditions, particularly in storms. As can be expected, modeling of such extreme events is highly dependent on accurate modeling of the wind field by the overlying atmospheric model and requires dynamic coupling of ocean, atmosphere and wave fields (Warner et al., 2010; Olabarrieta et al., 2012). Hegermiller (this workshop) points out that wave modeling is also limited by inaccurate parameterizations of wave breaking and wave–current interactions under strong wind conditions (Ardhuin et al., 2010). Inaccuracies in wave models under extreme conditions are accentuated by feedback into the atmospheric and ocean models to which they are coupled because of errors in predictions of air–sea fluxes under strong wave conditions including breaking (Zambon et al., 2014a; Allahdadi et al., 2019).

3.2. Numerical methods and modeling frameworks

3.2.1. A unified modeling framework

The sense that emerged from the workshop was that the existence of multiple on-going approaches to coastal and estuarine modeling is due to some basic challenges related to the coastal and estuarine parameter space. In contrast to the more unified modeling framework like that seen in the regional modeling community (i.e. ROMS), coastal and estuarine model applications are highly dependent on resolving bathymetric, coastline, and forcing variability, features that can be highly site specific. As a result, the community felt that it is important to ensure model diversity (see Table 1) to encourage application and testing of a wide variety of methods to understand resolution requirements related to the site-specific parameters. Despite the aversion to a unified modeling framework, there is a clear need for a common framework for model setup and analysis to reduce barriers for new users and facilitate more direct comparisons between approaches. Such a framework is sorely needed across all model classes, including coupled and uncoupled and structured and unstructured grids. The community felt there is a significant lack of standards for model coupling despite the wealth of coupled models. Similarly, a more unified approach to model inputs, including grid generation and boundary forcing files, would greatly reduce the overhead and expertise required to apply a new model to a particular problem.

In addition to simplifying the process of model implementation and analysis, a unified approach would significantly improve the ability to compare models. Model intercomparison would be encouraged because differences in model results depend critically on grid quality and accuracy of initial conditions, forcing and boundary conditions, features that are typically not highlighted in the peer-reviewed literature as much as parameterizations and numerical methods. Development of a unified framework would be a daunting task given the extensive variety with which users implement models, including compilers and operating systems, data formats (e.g. binary, NetCDF, etc...) and the scripts that are employed for model setup and analysis (e.g. bash, python, matlab, etc...). This variety is further complicated by the need to update software to ensure compatibility with continuous advances in software engineering tools.

3.2.2. A standard model test bed

Despite the importance of model diversity, there are few, if any, studies that systematically compare the accuracy and efficiency of different models to gain insight into their advantages and disadvantages. This is largely a result of the lack of a set of agreed upon benchmarks or test cases that can be applied to assess model performance.

It is standard practice to demonstrate model accuracy and efficiency through simplified test cases. As examples, the Thacker test case is standard for wetting and drying (e.g. Casulli, 2009), the lock exchange is standard for nonhydrostatic models (e.g. Fringer et al., 2006), and the channel flow, wind-driven mixed layer, and simplified estuary are standard cases for turbulence models (Warner et al., 2005). Although simplified test cases abound, they test model performance in regimes that are expected to give smooth or converged results, and so do not demonstrate model performance in scenarios that might be found in real problems. Simplified test cases also do not test model performance related to uncertainties in initial and boundary conditions. The lack of benchmarks for real problems is likely a result of the subjectivity related to choosing parameters for model setup. However, even if a model setup is consistent between two model implementations, there is substantial subjectivity in devising validation metrics to compare predictions to observations. For example, the skill score of Murphy (1988) is common in coastal modeling and normalizes the difference between model results and observations by a measure of the difference between the observations and a reference model, which is often taken as the mean of the observations or climatological values. While this is a reasonable metric since it implies that a model achieves a "better" skill score if the difference between the observations and reference model is greater, Hetland (this workshop) showed that there is subjectivity in defining the reference model, as it can require a time-averaged or low-passed signal about which the variance is defined. As a result, the skill score can vary significantly depending on how the error is normalized even if the absolute difference between the predictions and observations remains unchanged.

3.2.3. Higher-order accuracy

As they are currently implemented, coastal ocean models do not always take full advantage of higher-order accuracy. In this context, model accuracy is defined as the rate at which the error decreases with respect to spatial or temporal refinement. For example, a second-order accurate model is one in which the error decreases quadratically with respect to grid refinement. Here, the error can also be defined as the difference between the solution on one grid and the solution on a refined grid. It is important to note that deterministic chaos may prevent convergence with respect to spatial or temporal refinement, particularly when resolving horizontal spatial scales that are finer than the internal Rossby deformation scale. Therefore, strictly speaking, one would need to conduct grid refinement studies of ensemble average simulations. This would be prohibitively expensive from a computational point of view, and so refinement studies can realistically only be conducted on deterministic problems. Nevertheless, an advantage of using accuracy to gauge model fidelity is that, in principle, it does not require observations or "truth" because model accuracy is a test of whether the discrete equations converge to the exact governing partial differential equations. Therefore, although one model may be more accurate than another because it has more advanced numerical discretization techniques, this usually does not imply better agreement with observations owing to the dominance of errors related to forcing and boundary conditions. Furthermore, model accuracy is only assured when the spatial scales over which the solution varies are at least one order of magnitude larger than the grid spacing. Satisfying such a constraint requires grid resolutions and problem sizes that are beyond the reaches of existing computational resources. Therefore, most coastal applications are run with grid resolutions that allow grid-scale variability, resulting in grid-dependent solutions that are generally not expected to improve with grid refinement without calibration of tunable parameters.

Although the advantages of higher-order methods have not yet been exhibited for coastal problems, it is essential to employ at least second-order accurate flux-limiting schemes (both for finite-volume and discontinuous Galerkin methods) for scalar transport. First-order methods exhibit excessive numerical diffusion and cannot accurately predict physical processes with sharp horizontal gradients, such as gravitational circulation, river plumes, or other frontal processes. Despite their importance for scalar transport, flux-limiting schemes are not as important for momentum or continuity. Overall, it was agreed that, although models can vary widely in the discretization schemes, no model behaves as a second-order accurate model in practice because of the overriding uncertainties from the bathymetry and forcing. At best, spatial and temporal accuracy of coastal models is somewhere between first and second order, and in many cases spatio-temporal resolution is limited by the resolution of the boundary conditions and forcing and available observations for validation. Most importantly, high-resolution coastal models cannot be accurate without accompanying high-resolution, accurate bathymetry. Furthermore, accurate forcing is needed to accurately model the effects of such forcing. For example, the effects of the spatial variability of wind on estuarine circulation would not be possible without measurements of winds at many stations surrounding the estuary or accurate winds from an atmospheric model with sufficient resolution to resolve the spatial variability. Similarly, an accurate model also needs more detailed measurements for validation. For example, validation of flooding with an accurate coastal storm surge model is not possible without accurate water-level records during strong storm events, particularly in regions that are normally dry.

3.2.4. Finite-element vs finite-volume methods

Both the finite-element and finite-volume method exhibit the potential for grid-scale oscillations depending on mesh geometry and placement of discrete variables (Le Roux et al., 2007; Korn and Danilov, 2017). While the spatial accuracy of both methods is sensitive to mesh quality, in general the finite-element method is better suited to the development of higher-order spatial discretizations that are less sensitive to the grid. The spatial accuracy of the finite-volume method is typically restricted to first-order on general unstructured meshes, while second-order or higher accuracy can only be achieved on Cartesian or smoothly-varying curvilinear grids. Spatial accuracy of finite-volume methods can further degrade to less than first order on highly skewed meshes.

Although the finite-element method is more amenable to higher-order spatial discretization schemes, the finite-volume method is much more common in coastal modeling (See Table 1). The finite-volume method is more straightforward to implement and generally more computationally cost-effective because the finite-element method requires evaluation of costly numerical integrals and inversions of linear systems regardless of the time-stepping scheme (implicit time-stepping schemes require inversions of linear systems on both grid types). The finite-volume method also has the advantage that it can guarantee local conservation of mass, momentum, and energy, which is particularly attractive when enforcing monotonicity in scalar transport schemes. Finite-element methods, in contrast, generally ensure global rather than local conservation, although the discontinuous Galerkin formulation can ensure local conservation. Some models, such as SCHISM, employ the finite-element method to discretize the momentum equations and the finite-volume method to ensure mass conservation in scalar transport. Overall, the community agreed that there is no clear advantage of finite-volume vs. finite-element methods in existing popular coastal models.

Given that it is less susceptible to grid quality, the finite-element method is superior in the implementation of adaptive mesh refinement (AMR). As an example, since the discretization error in the discontinuous Galerkin method is related to jumps at element interfaces (Ainsworth, 2004), this error naturally serves as a metric for local mesh refinement where and when it is needed (Bernard et al., 2007). Mesh refinement via the addition or removal of elements is referred to as h-adaptivity, while refinement via movement of element nodes without changing the number of elements is referred to as r-adaptivity. While both finite-element and finite-volume models can employ h- or r-adaptivity, only finite-element methods can employ p-adaptivity, wherein the order of accuracy of the discretization is varied in time and space without altering the mesh. Examples of ocean models that employ AMR are the Imperial College Ocean Model (ICOM; Ford et al., 2004; Pain et al., 2005; Piggott et al., 2005) and the Nonhydrostatic Unified Model of the Ocean (NUMO), which is currently under development and based on the Nonhydrostatic Unified Model of the Atmosphere (NUMA; Giraldo and Restelli, 2008; Giraldo et al., 2010). Although the AMR approach is very powerful, it is not yet common for coastal modeling because mesh resolution is often known a-priori for most problems as it is dictated by bathymetry and coastlines (Ye et al., 2018). However, there is significant potential for application of AMR to coastal flooding problems in which large portions of the domain that are normally dry can be active during flooding. Even without AMR, the performance of parallel storm surge computations can be optimized with load balancing strategies that account for the large variability of active cells during flooding (Roberts et al., 2019). An important consideration related to high-resolution modeling of coastal flooding with AMR or high-resolution grids is the need for accurate bathymetry, vegetation and land use data in areas that are normally dry.

3.2.5. Tuning to account for unresolved processes and model error

It is well established that coastal models must be tuned to account for unresolved processes and numerical errors. Perhaps the most ubiquitous of the many subjective parameter choices in coastal models is the bottom roughness which dictates the bottom drag imposed on momentum and waves and the production of turbulence by bottom shear (see Section 3.1.2). The distribution of bottom roughness is not known either because the physical parameters are not known or measured or because of inaccurate or nonexistent parameterizations. The result is that most implementations require ad-hoc tuning of the drag parameters, particularly the bottom roughness, to improve model skill. Such tuning not only accounts for unresolved physical processes impacting the drag, but it also accounts for numerical errors. As an example, tuning of bottom roughness to account for numerical damping can lead to bottom roughness that is much smaller than the expected physical value since the numerical damping can overwhelm the physical damping. The optimal bottom roughness also depends on the grid resolution due to its effect on the numerical damping and on differences between the resolved and unresolved scales (e.g., Ralston et al., 2017).

Owing to the difficulty of predicting the distribution of vertical turbulent mixing as discussed in Section 3.1.1, it often requires tuning of several parameters. As an example, Ralston et al. (2017) simulated the circulation in a salt-wedge estuary with different bottom roughness coefficients, grid resolutions, and steady-state Richardson numbers. They were able to tune the bottom roughness to give the best skill scores for water levels and depth-averaged currents. However, a steady-state Richardson number of 0.1, which is smaller than the predicted value of 0.25 (See Section 3.1.1) was needed to give good model skill for baroclinic features in frontal regions to compensate for excess numerical mixing. Because the excess numerical mixing decreased with grid refinement, the required steady-state Richardson number increased, although it was estimated that a prohibitively high horizontal grid resolution of about 5 m would be needed to require the theoretically correct value of 0.25. These results suggest that the steady-state Richardson number is not a tuning parameter in the classical sense. Unlike the bottom roughness parameter, there exists a grid resolution at which it is no longer justified to tune the steady-state Richardson number in a RANS modeling framework because, in principle, the mean shear and stratification can be resolved (a steady-state Richardson number parameterization is not needed for LES; see Section 3.2.10).

Tuning of the bottom roughness or other parameters like the steady-state Richardson number to produce higher skill scores accounts for errors in both the parameterizations and numerical methods. For scalar transport, the principal error is numerical diffusion which can incur mixing that is larger than the physical mixing. Although higher-order methods help to reduce spurious numerical diffusion, in practice models exhibit near first-order error in the presence of sharp fronts or around grid-scale bathymetric variability. The significant role that numerical diffusion plays in the distribution of mixing throughout an estuary makes it difficult to assess turbulence model performance because it is difficult to compare the vertical mixing computed by the model to the observed turbulent mixing. Recently, finite-volume methods have been developed to compute the spatio-temporal distribution of numerical mixing (Burchard and Rennau, 2008; Klingbeil et al., 2014) which allows for a direct quantification of the amount of numerical relative to physical mixing. The methods are non-invasive in that they can quantify numerical mixing with minimal code alteration and can be applied for structured and unstructured grids in a finite-volume framework. Results from several estuarine models at the workshop showed that a significant fraction of the mixing was numerical, with the numerical mixing being greater than the physical mixing in some cases. Numerical diffusion in a model is highly dependent on the grid resolution, numerical schemes being used, and strength of material property gradients (e.g., bathymetry, velocity, salinity) being simulated. Although the notion of reducing the numerical mixing to a level that is smaller than the physical mixing poses a daunting challenge for coastal models in terms of resolution requirements, such a challenge would be impossible without the ability to quantify the numerical mixing using methods like those developed by Burchard and Rennau (2008) and Klingbeil et al. (2014).

3.2.6. Grid generation and placement of variables

The most important yet underappreciated aspect of coastal modeling is development of the computational grids. Grid generation is in some ways more difficult for structured, curvilinear grids given the need for smoothness in curvilinear grids. There are many grid generation tools for both unstructured and structured models (e.g. Gmsh, gmsh.info - Geuzaine and Remacle, 2009; SMS, aquaveo.org; Janet, smileconsult.de), yet there is no clear advantage of one over the other because grid generation continues to be a largely manual or tunable process. Grid resolution fundamentally dictates the accuracy and efficiency of the results, yet grids can never fully resolve the complexity of the bathymetry and coastline in coastal problems. In general, unstructured grids are better at resolving complex bathymetric features than curvilinear or Cartesian grids, and unstructured grids can also more efficiently resolve multiscale features due to the flexibility of grid orientation and telescoping. A good example of the advantage of unstructured meshes is the finite-element model of the Great Barrier Reef using SLIM (Second-generation Louvain-la-Neuve Iceocean Model; Vallaeys et al., 2018), which resolved the flow features throughout the detailed reef system with an extremely complex, high-resolution mesh (Legrand et al., 2006; Lambrechts et al., 2008). To avoid significant grid stretching when using structured grids, grid nesting must be used, wherein grids with successively finer resolution are nested within one other (e.g. ROMS-AGRIF; romsagrif.gforge.inria.fr). Nesting enables use of smaller time-step sizes on the finer grids, thus reducing the number of time steps and the associated computational cost on the coarse grids. It is possible to employ smaller time-step sizes where cells are finer on single grids with the multirate approach as applied to the SLIM model (Seny et al., 2013). However, this method is difficult to implement and is not common in coastal ocean models.

Although some effort has been made recently to more objectively construct grids and to ensure reproducibility (Candy and Pietrzak, 2018), generation of structured or unstructured grids is not fully automated because both require subjective decisions related to manual grid alteration in regions with degraded grid quality. An additional advantage of unstructured grids is that grid edges are constrained to follow a specified coastline and so no masking is required to eliminate inactive cells over land from the computation. This has the advantage that no memory or computational effort is wasted on masked cells. More importantly, however, the process of grid masking is typically a manual process since it requires decisions about which grid cells will account for unresolved features such as narrow channels or headlands. While unstructured grids do not need grid masking, grid quality still typically degrades around complex bathymetric features since grids must be highly skewed when constrained by sharp coastline angles or grid-scale bathymetric features. Either way, both structured and unstructured grids require manual intervention in which grid nodes are moved to improve grid quality at the expense of poorer coastline resolution, although finite-element methods are more forgiving, as discussed below. The need for masking can be eliminated with use of subgrid bathymetry (Casulli, 2009), a method that employs bathymetric resolution that is finer than the grid to ensure that the cell geometry follows the bathymetry without constraining the grid edges to follow coastlines (see Section 3.2.7).

In general, finite-element methods are less sensitive to grid quality, and so most finite-element models can be run with little to no grid tuning. Finite-volume methods can be highly sensitive to grid quality depending on arrangement of the variables on the grid. On staggered, or C grids (Arakawa and Lamb, 1977), pressure gradients are defined as normal to grid edges and are computed as the difference between the pressures at cell centers on either side of the edges. Therefore, C grids must be orthogonal so that the lines connecting cell centers, or Voronoi edges, are perpendicular to lines connecting cell vertices, or Delaunay edges. Generation of high-quality orthogonal grids is extremely difficult when constrained by complex coastlines. This can be alleviated with hybrid unstructured grids that can employ arbitrary-sided cells, thus allowing resolution of channelized features with quadrilateral grid cells and connecting the quadrilateral regions with triangles or other polygons (e.g. MacWilliams et al., 2016; Ye et al., 2018). However, there are no automated grid generation tools that employ both triangles and quadrilaterals. Other grid arrangements such as A (all variables are collocated at cell centers) or B (velocity components stored at cell vertices) grids alleviate the orthogonality constraint, although no popular coastal models employ A grids because they tend to exhibit grid-scale noise due to decoupling between the pressure and velocity (Danilov, 2013). The FVCOM model employs B grids and is one of the most robust coastal models regarding susceptibility to grid quality, while the SCHISM model avoids grid quality issues associated with C grids by employing finite-element methods for the momentum equations. Owing to the problem of grid-scale noise on A grids, except for FVCOM, all popular regional or coastal models employ C grids, ROMS being the most obvious example (see Table 1). Interestingly, weak grid-scale noise is also a feature of unstructured, triangular C grids (Korn and Danilov, 2017), and it can be amplified by poor grid quality (Wolfram and Fringer, 2013). However, such noise is manifested in weakly dissipative settings over time scales that are much longer than those typically employed in coastal models (Danilov, 2013). Hexagonal C grids are a viable alternative that eliminate the noise, although they can be difficult to generate in complex coastal geometries and have been better suited to global ocean modeling (Ringler et al., 2010).

3.2.7. Subgrid bathymetry

Recent advances in bathymetric surveying have enabled extremely high-resolution bathymetry at sub-meter resolutions for entire coastal regions. For example, a digital elevation map is available for the entire country of the Netherlands at a horizontal resolution of 0.5 m (http://www.ahn.nl). Such high-resolution datasets provide bathymetry that will continue to be substantially higher than typical grid resolutions of coastal models for the foreseeable future. With bathymetric resolution that is higher than the grid resolution, typical coastal models subsample the bathymetry data through averaging to assign model depths at cell centers or edges while ensuring the same water volume relative to some datum on the subsampled bathymetry (e.g. Ye et al., 2018). Subsampling eliminates information about the high-resolution, or subgrid, bathymetry that can be used to inform a more accurate simulation. In the two-dimensional subgrid bathymetry method of Casulli (2009) (adapted to three dimensions by Casulli and Stelling, 2010), the finite-volume framework uses the bathymetry data within a grid cell to obtain a more accurate representation of the cell geometry, such as volume, surface area, and cross-sectional area of cell faces. As a result, the cell geometry is independent of the computational grid resolution since it is only a function of the bathymetric resolution.

Combined with more accurate volume and mass fluxes, in most cases the subgrid method gives accurate solutions at a reduced computational cost because the computational grid can be coarsened without sacrificing accuracy related to the subgrid representation of the bathymetry. As an example, MacWilliams et al. (2016) simulated the San Francisco Estuary in three dimensions using the UnTRIM model with the subgrid method of Casulli (2009) and achieved similar accuracy as a previous, high-resolution simulation (MacWilliams et al., 2015) with one order of magnitude fewer cells in the horizontal and a decrease in run time by a factor of 40. Similarly, Sehili et al. (2014) observed speedup by a factor of 20 using UnTRIM with subgrid bathymetry to simulate the Elbe Estuary. In addition to reduced computational cost, the subgrid method also relieves the constraint on grid quality since grid boundaries do not need to be aligned with coastlines because the subgrid bathymetry ensures accurate geometric representation regardless of grid orientation. As a result, the subgrid method allows a three-dimensional model to resolve channels with one grid cell in the cross section, effectively providing for seamless transition between three- and one-dimensional modeling within the same framework. This was demonstrated by Stelling (2012) and Sehili et al. (2014), who show that subgrid modeling can resolve channels with one grid cell accurately as long as the cross-channel variability in the friction term is appropriately accounted for in a way that gives the correct flow–stage relationship. An additional advantage of the subgrid bathymetry method is that it eliminates the stability restriction associated with wetting and drying, thus further increasing computational efficiency by allowing larger time-step sizes (Casulli, 2009). While subgrid bathymetry can reduce the computational cost of computing flow and stage in channelized networks, subgrid bathymetry may not necessarily give more accurate results for features with strong horizontal variability such as salt wedges, fronts, or flow features arising from strong cross-channel bathymetric variability (Zhang, 2017). Accurate computation of these processes requires higher resolution of the base grid.

3.2.8. The vertical coordinate system

It is often argued that sigma-, s-, or in general terrain-following vertical coordinates should be employed to accurately resolve along-bottom flow in contrast to z-levels or Cartesian vertical coordinates that represent bottom topography with stair steps. The stair steps give rise to grid-scale variability in flow variables which can induce spurious numerical mixing (Legg et al., 2006) and also lead to discontinuities in the bed shear stress (Platzek et al., 2014), which can be particularly problematic for sediment transport. Another problem with z-levels arises in the presence of large changes in water level due to strong tides, which requires that the free surface cross over grid lines if sufficient vertical resolution is desired throughout the tidal cycle in shallow areas. Otherwise, shallow areas might be resolved with just one grid cell in the vertical while deeper areas are resolved with many more. Despite these problems, unlike sigma coordinates, z coordinates do not exhibit the well-known pressure gradient error, particularly in the presence of steep bathymetry (Shchepetkin and McWilliams, 2003). The pressure gradient error is more problematic in coastal problems containing the shelf break, seamounts, or canyons. It is typically less of a concern in estuaries where tidal currents are generally stronger than currents induced by the pressure gradient error and horizontal pressure gradients are weaker owing to stronger mixing and shallower water.

Most popular coastal models employ sigma coordinates (see Table 1) except for UnTRIM and SUNTANS, which employ z coordinates (see Table 1). The stair-stepped nature of z-levels can be reduced with partial stepping, whereby the bottom face of the bottom-most cell coincides with the bed, or shaved cells (Adcroft et al., 1997), in which the numerical discretization is rewritten about finite-volume cells that are “cut” by the bathymetry so that one of the faces is coincident with the bed. Discontinuities in the bottom shear stress when using z-levels can be avoided with remapping, in which the velocity is remapped onto a terrain-following grid at each time step to produce a continuous along-slope velocity field and bottom stress distribution (Platzek et al., 2014). The subgrid bathymetry method (see Section 3.2.7) can also be applied to improve the representation of the bottom bathymetry when using z-levels. Practically speaking, terrain following coordinates are more straightforward from a coding perspective because the number of active layers in the vertical is constant in time and space.

Although the apparent advantages of each type of vertical coordinate are readily exhibited with idealized test cases, there is no clear winner when applied to real coastal problems. This is likely a result of other errors that make it difficult to quantitatively compare numerical discretization errors, as discussed in Section 3.2.3. Nevertheless, some models have shown great promise in application of hybrid vertical coordinates, such as SELFE, which employs terrain-following coordinates in the upper layers of the water column and z-levels at depth (Zhang and Baptista, 2008), or SLIM, which can employ a combination of (fixed or adaptive) z and (generalized) sigma coordinates (Delandmeter et al., 2015, 2018; Vallaeys et al., 2018). Hybrid vertical coordinate models are advantageous in estuaries with broad shoals and gradual bathymetry in the shallows, which is appropriate for sigma-coordinates, while z-levels are employed in deeper regions where slopes may be steeper, thus avoiding pressure gradient errors. To reduce pressure gradient errors while retaining the advantages of both z- and terrain-following coordinates, the SCHISM model (Zhang et al., 2015) employs localized sigma coordinates with shaved cells (LSC^2), wherein the slope of the sigma coordinates in the presence of steep slopes is reduced by adding more vertical layers near the bed.

Despite the benefits of hybrid vertical coordinates, all vertical coordinate approaches in popular coastal models exhibit spurious vertical numerical diffusion of scalars. Although numerical diffusion is reduced with LSC^2 vertical coordinates, the optimum approach is to employ arbitrary Lagrangian–Eulerian vertical coordinates (ALE; Adcroft and Hallberg, 2006). In the ALE approach, the vertical coordinate moves with the flow via Lagrangian trajectories followed by a correction to prevent grid distortion (e.g. Burchard and Beckers, 2004; Hofmeister et al., 2010; Delandmeter et al., 2018). In this way, the vertical coordinate can naturally follow one or a combination of z-levels, s-levels, or isopycnal coordinates. Isopycnal coordinates, by definition, eliminate vertical numerical diffusion of scalars because there is no transport of scalars across isopycnal coordinate lines and hence no discrete vertical advection. Isopycnal coordinates are not well suited to coastal simulations given that there can be significant physical mixing and isopycnals are vertical at fronts. However, ALE coordinates can be moved adaptively (r-adaptivity; see Section 3.2.4) to concentrate vertical coordinates in regions with strong stratification, thus encouraging representation of sharper vertical density gradients. Quantification of spurious numerical diffusion with the techniques of Burchard and Rennau (2008) and Klingbeil et al. (2014) shows significant reduction of numerical mixing in coastal problems when using ALE vertical coordinates (Gräwe et al., 2015).

3.2.9. Nonhydrostatic modeling

Coastal models are typically hydrostatic because most processes of interest have long horizontal scales of motion relative to the vertical scales (Marshall et al., 1997b). The nonhydrostatic pressure is important only when considering processes that are short relative to the depth. In order of decreasing horizontal scales, these include solitary-like internal gravity waves, fronts and bores, surface gravity waves, convective overturning, Kelvin–Helmholtz like billows, flow over short-wavelength topography (including small-scale roughness, such as dunes, ripples, vegetation, etc. . .), and turbulence. Resolving such processes in coastal domains is computationally expensive because it requires very high resolution of the order of meters or smaller. It is even daunting to resolve horizontal scales associated with internal solitary waves, which are likely the largest scales for which the nonhydrostatic pressure is important. In this regard, the horizontal grid resolution must be smaller than the depth of the mixed layer in order to resolve the internal solitary wave dispersion (Vitousek and Fringer, 2011), which requires O(1 m) grid resolutions in coastal problems.

The nonhydrostatic pressure is computed in many coastal and regional ocean models, including MITgcm (Marshall et al., 1997a), TRIM (Casulli, 1999), UnTRIM (Casulli and Zanolli, 2002), SUNTANS (Fringer et al., 2006), ROMS (Kanarska et al., 2007; Auclair et al., 2018), FVCOM (Lai et al., 2010a), and GETM (Klingbeil and Burchard, 2013). At smaller scales needed to resolve dispersion related to surface gravity waves, several three-dimensional nonhydrostatic models have been developed, such as SWASH (Zijlema et al., 2011) and NHWAVE (Ma et al., 2012; Shi et al., 2015). In addition to the computational cost associated with the large number of grid cells needed to resolve nonhydrostatic effects, computation of the nonhydrostatic pressure is expensive because it requires solution of an elliptic equation which can increase the computational cost of a coastal simulation by more than one order of magnitude. Fortunately, because nonhydrostatic processes occur over short length scales, they encompass a small fraction of the energy in most coastal problems and thus computation of the nonhydrostatic pressure may not necessarily show significant improvement of predictions over time scales greater than O(1 hr). Unresolved nonhydrostatic processes like convective overturning or shear instabilities are represented reasonably well by RANS turbulence closure schemes, despite the need for tuning, as discussed in Section 3.2.5. Even the propagation speed of, for example, river plume fronts and short internal gravity waves are reasonably well predicted with hydrostatic models given that these propagate close to the hydrostatic, long-wave speed. Only when the details of such processes are of interest is the nonhydrostatic pressure important.

Because of the relatively weak impact of small-scale nonhydrostatic processes on large-scale flows, most nonhydrostatic studies are conducted in idealized domains. Most of these idealized studies are conducted in small domains so that the nonhydrostatic effects are dominant. Few studies have resolved small-scale physics and their effects on large-scale processes with a nonhydrostatic model. Examples include the study of Shi et al. (2017), who used the nonhydrostatic NHWAVE model to simulate the structure of a front near the mouth of the Columbia River to resolve the details of fine-scale, nonhydrostatic features apparent in airborne imagery. Other field-scale, nonhydrostatic examples include simulation of nonlinear and nonhydrostatic internal waves in Massachusetts Bay by Lai et al. (2010b) and sediment resuspension by internal bores in Otsuchi Bay, Japan, by Masunaga et al. (2017). Despite the realistic scales of these simulations, only qualitative comparisons with field observations could be made because of the idealizations.

3.2.10. Large-eddy simulation (LES)

In principle, a coastal model could directly compute the turbulent scales of motion and eliminate the need for a turbulence model if it were nonhydrostatic (since the turbulent scales are nonhydrostatic) and the grid resolution was sufficient to resolve the turbulent scales of motion. This could be accomplished with a direct-numerical simulation (DNS), for which the grid must resolve all of the turbulent scales of motion. However, DNS is not feasible in coastal flows given that the grid spacing must be on the order of the Kolmogorov dissipative scale (or the Batchelor scale, if there is scalar transport), which implies the need for an unrealistic number of grid points (see, e.g. Pope, 2000, Ch. 9). The computational cost can be alleviated with a large-eddy simulation (LES) in which the energy-containing eddies are resolved by the grid and the small, or subgrid-scale eddies, are parameterized with a so-called subgrid-scale (SGS) or subfilter-scale (SFS) model (Pope suggests that 80% of the turbulent kinetic energy should be resolved). The degree to which the computational cost is reduced for LES when compared to DNS depends on the flow of interest. Near boundaries, the computational cost of LES is still extremely high because of the need to resolve the small near-wall turbulent scales that are proportional to the viscous wall unit ν/u_*, where u_* is the friction velocity. To avoid the computational cost of resolving boundary layers, the LES can simulate the region away from the wall and parameterize the near-wall region and the associated stress with so-called wall-layer modeling (Piomelli and Balaras, 2002). Avoiding simulation of the near-wall region decreases the needed grid resolution roughly by a factor of 10 in each direction, leading to substantial savings in computational cost and the ability to simulate higher Reynolds numbers (Piomelli and Balaras, 2002). As an example, Chou and Fringer (2008) simulated suspended sediment transport in a channel with a Reynolds number of 600,000 (based on the channel height) using LES. Because the near-wall physics were not resolved, the wall stress was modeled with a quadratic drag law and the near-wall vertical turbulent Reynolds stress was augmented with the model of Chow et al. (2005). The augmented stress ensures that the near-wall eddies are strong enough to vertically mix momentum to produce the correct mean logarithmic velocity profile. An important constraint with this approach is the need for the first grid cell to fall within the lower end of the logarithmic velocity profile, implying that the first grid point must be within roughly 10–100 wall units of the boundary (Piomelli and Balaras, 2002). This is similar to the requirement for RANS-based coastal modeling when the velocity in the bottom-most grid cell is constrained to match the log law (See Section 3.1.2). However, unlike in RANS-based coastal modeling in which horizontal grid resolutions are typically O(100 m – 1 km), the horizontal grid resolution in LES is constrained by the need for the grid aspect ratio to be as close to unity as possible. Otherwise, the accuracy will degrade due to numerical errors related to the SGS parameterization (Scotti et al., 1993) and the nonhydrostatic pressure solver (Fringer et al., 2006; Santilli and Scotti, 2011). The accuracy of numerical methods used to discretize the governing equations also dictates the grid resolution in LES, an effect that is accentuated by high aspect ratio grids. The importance of numerical methods in LES is discussed by Rodi et al. (2013), who emphasize that central schemes for momentum advection should be used in LES given that upwind-biased schemes often produce too much numerical dissipation, leading to an incorrect prediction of the turbulent kinetic energy spectrum.

Although the cost of LES is generally lower in regions where boundary layers are absent or not important, stable stratification can also require high resolution for LES, since the grid resolution in the presence of stable stratification must resolve the Ozmidov scale, or the largest scale of turbulence before internal wave motions dominate. The ratio of the Ozmidov scale to the Kolmogorov scale is proportional to $Re_b^{3/4}$, where $Re_b = \epsilon/(\upsilon N^2)$ is the Buoyancy Reynolds number with dissipation ϵ and buoyancy frequency N (e.g. Smyth and Moum, 2000). With Re_b as small as O(1) in the ocean thermocline (Ivey et al., 2018), the resolution requirement based on the Ozmidov scale in stably stratified boundary layers with LES can be as limiting as resolving unstratified turbulent boundary layers. This is a well-known limitation in LES of stable atmospheric boundary layers (Chow et al., 2005). If the flow is well-mixed (i.e. there is no stratification) and boundary layers are not important or can be modeled, the grid resolution needed for LES is less dependent on the Reynolds (Pope, 2000) or buoyancy Reynolds numbers, and instead is based on the need to resolve the energy-containing scales of motion that are dictated by the problem of interest. For example, Langmuir cells in the surface mixed layer can be simulated accurately with LES if 10–20 grid points are used to resolve each Langmuir cell (Skyllingstad and Denbo, 1995). Similarly, the convective atmospheric boundary layer is simulated accurately using LES if the boundary layer is resolved with at least 50 grid points in the vertical (Sullivan and Patton, 2011).

Although wall models can be used to parameterize near-wall physics, simplified parameterizations like quadratic drag laws that are often used in wall modeling cannot account for the more complex dynamics associated with flow separation or stratification. A novel method to reduce the cost of LES in the presence of walls while retaining more complex near-wall physics is to employ hybrid RANS-LES approaches, such as detached-eddy simulation (DES; Rodi et al., 2013). In this approach, the near-wall region is modeled with a RANS approach (See Section 3.1.1), while the far-field region is simulated with LES. The subgrid-scale model in the LES uses a similar eddy-viscosity parameterization as the RANS model, except that the length scale in the LES model is proportional to the grid resolution. As examples, in the DES simulations of realistic river geometries of Constantinescu et al. (2011a,b), LES was applied away from the walls to simulate the large-scale flow separation and circulation, while the turbulence in the hydraulically-rough, near-wall regions was parameterized with the Spalart–Allmaras (SA) one-equation model (Spalart, 2000), which only requires the near-wall length scale to parameterize the eddy-viscosity (as opposed to the two-equation models discussed in Section 3.1.1).

While hybrid RANS-LES approaches and wall models are promising, their application to coastal modeling is fundamentally limited by a lack of knowledge of the near-wall physics, which is ultimately stochastic in nature and not only difficult to model but also extremely difficult to measure. Therefore, much of the uncertainty inherent in the traditional RANS approach to coastal modeling discussed in this paper would not be eliminated with LES modeling since it would still require tuning of unknown coefficients related to the parameterizations of near-wall physics. Notwithstanding the difficulty with boundary conditions, however, the primary advantage of LES modeling would be a direct calculation of turbulence away from boundaries, thus eliminating the need to parameterize highly unsteady or stratified turbulence, processes that can require tuning in a RANS framework (See Section 3.2.5).

3.3. Field observations

Field observations form an integral component of modeling because they are needed for initialization, forcing, and validation. This is particularly true for data assimilation and operational modeling, as pointed out in the summary of the IOOS-sponsored workshop on operational ocean modeling by Wilkin et al. (2017). Regarding forward and process modeling, high-resolution field observations are an essential component of understanding of physical processes that in turn leads to the development of improved parameterizations and modeling techniques. Like models, 'observations' are subject to errors and uncertainties and they are frequently 'modeled' from the raw measurements.

3.3.1. New instrumentation techniques

Among the many exciting new instrumentation techniques, Reid et al. (2019) discuss measurements of nonlinear internal wave activity on the Donghsa Atoll in the South China Sea using the distributed temperature sensor (DTS), a 4 km long cable resting on the bed that recorded temperature every minute at a spatial resolution of 2 m. While the most obvious benefit of such measurements is the ability to understand the details of high-frequency processes related to nonlinear internal waves, an additional advantage is that they lead to the development of high-resolution simulations needed to understand those processes. High-resolution simulations would otherwise be difficult if not impossible without the necessary high-resolution observations needed for validation. Davis (this workshop) presented results of high-resolution, nonhydrostatic simulations using the SUNTANS model that were used to help interpret the high-resolution observations, which in turn were used to validate the model.

Acoustic instruments to measure velocity like the acoustic Doppler current profiler (ADCP), which measures mean current profiles over the water column, and the acoustic Doppler velocimeter (ADV), which measures high-frequency currents (i.e. turbulence) at a point, have been in use for several decades. Recent developments in acoustic instrumentation include the vectrino profiler, which measures currents, turbulence, and SSC in 1 mm bins over 3 cm and can thus yield flow details within O(1 cm) boundary layers in the environment (e.g. Wengrove and Foster, 2014; Brand et al., 2016; Egan et al., 2019). These detailed measurements can be used to directly test bottom stress and erosion parameterizations of wave–current boundary layers in real field settings (See Sections 3.1.2 and 3.1.3). To broaden the parameter space and help develop parameterizations, those detailed measurements can be compared to DNS and LES studies. This presents a huge leap in our ability to use DNS and LES to develop parameterizations in real, field-scale settings. Such simulations have been restricted to laboratory-scale experiments that until now were the only setting in which high-resolution measurements like those with the vectrino could be obtained.

3.3.2. Remote sensing

Advances in high-resolution remote sensing technologies are continuously increasing the resolution with which coastal processes can be measured. For example, Giddings (this workshop) presented research on the large-scale impacts of small-scale coastal streams and the resulting plumes, work that is motivated in large part by high-resolution satellite remote sensing (e.g. Warrick and Farnsworth, 2017). Although the high-resolution imagery provides spatial detail, models are needed to study the associated high-frequency temporal resolution, such as the high-resolution simulations of Romero et al. (2016) which employed ROMS with four nested grids (the finest had a resolution of 100 m) to study the dispersion of a small river plume near Santa Barbara, CA. This resolution resolved the features of the submesoscale eddies and their interaction with the river plume, although Giddings and colleagues (this workshop) are employing ROMS nesting with a fifth nested grid that has 10 m horizontal resolution to study surf-zone dispersion by waves interacting with the Tijuana River plume near San Diego, CA. These high-resolution simulations are only possible with companion high-resolution observations, such as the aerial imagery and high-speed jet-ski transects employed by Hally-Rosendahl et al. (2014) or the infrared imagery by Marmorino et al. (2013) to study surf-zone dispersion. Detailed observations like these form the impetus for the high-resolution simulations of transient rip currents by Kumar and Feddersen (2016, 2017) discussed in Section 3.1.5. In a similar manner, Shi et al. (2017) used the nonhydrostatic NHWAVE model with high horizontal resolution to understand the source of thermal fingers observed in aerial infrared imagery obtained at the mouth of the Columbia River.

In addition to infrared remote sensing which reveals structures with a thermal signature, recent remote sensing technologies have been developed to measure surface deflections with high spatial resolution, as in the airborne LiDAR measurements of Branch et al. (2018), which could measure surface wave features at the Columbia River mouth with O(0.5–1.0 m) horizontal resolution. Structured from motion (SfM) photogrammetry using airborne drones (Dietrich, 2017) is an exciting new technology to remotely measure high-resolution bathymetry. SfM methods can be used in combination with interferometric multibeam acoustic surveys to greatly increase the coverage and resolution of bathymetric data in shallow regions that are challenging to survey with traditional multibeam or single beam acoustic methods.

3.3.3. Acoustic backscatter

Recently, methods have been devised using the backscatter signal from acoustic profilers to measure the vertical structure of flow, density, and SSCs at extremely high resolution in coastal flows (Geyer et al., 2013). For example, Geyer et al. (2010) studied the dynamics of stratified shear instabilities in the Connecticut River estuary with a high-resolution broadband echo sounder that measured turbulent processes over vertical scales of O(10 cm), in combination with ADCPs and ADVs to measure velocity. Horner-Devine and Chickadel (2017) used infrared imagery to measure the surface features with O(1 m) scale instabilities at the front in the Merrimack River plume, and these measurements were combined with subsurface backscatter measurements using ADCPs to infer the three-dimensional structure of the instabilities and show that they are similar to lobe-cleft instabilities found in gravity currents. Such high-resolution field measurements naturally motivate high-resolution, nonhydrostatic simulations to further understand the underlying physics.

3.4. High-performance computing

The coastal ocean models in use by the community today have been parallelized to some degree, either using distributed memory message-passing techniques such as MPI and/or shared memory tools such as OpenMP. It is well recognized that models that employ explicit methods in time or have simple matrix solves (e.g. symmetric and diagonally dominant) are typically easier to parallelize as they avoid the solution of potentially ill-conditioned systems of linear and nonlinear equations commonly found in implicit methods. However, implicit solvers have become much more sophisticated in recent years, with open-source packages such as PETSC now in wide use, making them competitive for large-scale parallel computing. Typical coastal models running large scale applications can scale to 100s or 1000s of cores on today's supercomputers.

As supercomputer architectures evolve, with Graphical Processing Unit (GPU) machines becoming more prevalent, and hybrid CPU/GPU machines coming online, the algorithmic techniques must also evolve. Typical lower-order methods in use today in most codes will probably not scale well on these machines, due to low memory access to compute ratios. Higher-order methods may actually perform better, since more work is performed per cell, meaning more local memory access. However, the difficulties with higher-order methods mentioned in Section 3.2.3 make this a challenging research area. Still, if the coastal modeling community is going to play in the 'exascale' computing arena of the future, these challenges must be tackled head-on, and soon.

Another high-performance computing (HPC) arena that is rapidly evolving is the use of cloud computing. Cloud computing, at least as it pertains to physics-based simulations, is still in its infancy. And, while NSF has funded cloud computing based research under some of its 'big data' initiatives, it remains to be seen what impact it will have on the coastal modeling community. However, cloud computing opens up entirely new frontiers in making computing resources available and more affordable to a larger community, and will most certainly have a larger role in the future of HPC.

Finally, physics-based simulators are becoming simply one part of simulation frameworks that merge big data, uncertainty quantification and parameter estimation, statistical inverse methods, data assimilation, and machine learning tools. In these frameworks, the simulator must often be executed tens to hundreds of times in order to generate statistical quantities of interest conditioned on uncertain data. To be scalable and efficient, these frameworks must utilize HPC, and the physical-based simulators must be optimized for performance. The merging of data science tools with physics-based simulation in HPC environments is another new frontier for the coastal modeling community to explore. As our sources of data continue to advance at a rapid pace, we must learn how to best utilize the data to improve predictive simulations.

4. Recommendations

4.1. Collaboration, engagement, and education

Different groups within the coastal modeling community should more closely collaborate. The original date of this workshop conflicted with the 15th Estuarine and Coastal Modeling Conference (ECM15) which was held in Seattle, WA, June 25–27, 2018. Despite the relevance of that workshop to the goals of this workshop, it posed a conflict for just one of the forty invitees to our workshop. This is indicative of the lack of communication in the coastal modeling community, which appears to be divided into three groups: (1) Those working on development and application of forward models and process studies (predominantly participants of this workshop), (2) those working on assimilative models and state estimation techniques, and (3) operational or applied modelers (ECM15, including modelers from both academia and industry). Within these groups, there are workshops and conferences with even more specificity, such as focused workshops on data assimilation or unstructured grids (e.g. IMUM — International workshop on Multi-scale Unstructured mesh numerical Modeling for coastal, shelf, and global ocean dynamics). While such specificity is natural and should be encouraged, the community should also focus on workshops and collaborative initiatives that foster interaction of the different groups. Most importantly, there is scant interaction between the forward and inverse modeling communities, despite the importance of inverse methods in improving forward modeling capabilities and process studies. Similarly, limited interactions between unstructured and structured grid or finite-element and finite-volume communities represent missed opportunities to synergistically address common problems in model development and application to what are often the same coastal regions.

The coastal modeling community should engage with the applied math, computer science, and HPC communities. The lack of communication between the different groups within the coastal modeling community extends to a lack of communication between the coastal modeling community and the applied math and HPC communities. Coastal modeling can benefit significantly from the recent surge of methods in machine learning, parameter estimation, and inverse methods which can be used to quantify uncertainty and incorporate high-resolution in-situ and remote-sensing techniques for improved predictions and parameter estimation into coastal ocean models (See Section 4.5). Funding agencies should consider proposal calls which foster such engagement. For example, The Collaboration in Mathematical Geosciences program was an NSF-sponsored program that funded research collaborations between coastal modelers and applied mathematicians and led to the development of many of the techniques presented at this workshop.

Academic programs should promote more applied math and computer science in their curricula. The lack of collaboration between different groups in the coastal modeling community can be attributed to the academic backgrounds of those involved. For example, the prevalence of finite-volume over finite-element methods in coastal modeling is likely because traditional curricula in physical oceanography or coastal engineering focus on finite-difference or finite-volume methods because those require less mathematical background than finite-element methods. Similarly, data assimilation and machine learning techniques also require strong backgrounds in applied mathematics and computer science. The coastal modeling community should integrate such methods into curricula to train the next generation of coastal modelers.

Because coastal models have become sufficiently robust and accessible over recent decades, scientists and engineers can now use coastal models in their research without having to develop their own codes or understand the details of a particular numerical method. This precludes the need, in many cases, for coastal modelers to learn the applied math and computer science details involved. However, academic programs should broadly train students in the underlying principles and tradeoffs of different modeling approaches, and introduce methods by which they might apply models to particular problems, for example using the common framework described in the next section.

4.2. A common framework for model setup, validation, and intercomparison

Discussions at the workshop focused extensively on model intercomparison to aid in model selection for a particular application and to assess accuracy of numerical methods, model efficiency, and the effectiveness of parameterizations employed in the models. However, it was noted that model implementation for real coastal problems requires many subjective choices that make it difficult, if not impossible, to quantitatively compare or reproduce results. These subjective choices include, for example, the bathymetric resolution, the structure of the grid, model forcing datasets, parameterization schemes, numerical method options, etc… Attempts to compare these different choices are difficult because they are generally not documented in academic papers, largely because few if any scientific or engineering journals encourage publication of site-specific modeling studies with technical details needed to reproduce model results. Instead, academic papers focus on general descriptions of model setup with an emphasis on model validation that is also highly subjective. This suggests an opportunity for the community to be more open to publications related to site-specific model implementation and to give more credit for publications in technical journals. Of course, a paper with all of the technical details related to a model application would be too boring for words. Therefore, the community should embrace the open-source model and use code repositories like GitHub to promote completeness and transparency related to specific model applications. Although code repositories are common platforms to share source code for the models themselves, it is rare to find references to repositories related to actual model applications in papers. An added advantage of code repositories is the ability for individuals to modify model parameters and input data and post results of different implementations to the repository so that they can be made available to the community.

We note that academic papers focusing on numerical methods (as opposed to model applications) usually include details needed to reproduce the test cases. However, these test cases typically do not require subjective user choices because they are often simplified and designed to accentuate the behavior of a specific aspect of a model. They also typically do not incorporate the spatial and temporal complexity of a realistic application.

To promote quantitative assessment of different models, the community should develop a set of guidelines on how to report details related to coastal model implementation. These details should include a list of all model parameters and subjective choices needed to reproduce the results, including validation metrics and related data. In addition, the guidelines should promote sharing of datasets needed to initialize and force the models, such as bathymetry, grid, wind data, tidal data, flow data, etc… Ultimately, it would be up to the community to define a set of standard reporting protocols to ensure all details needed to reproduce a model result are available. These details would also include observational data used for model validation and the details of how validation metrics were created. To encourage unified reporting of these model details, the community should encourage proposal writers to document reporting strategies in, for example, the NSF Data Management Plan.

To promote model intercomparison, the community should agree on a set of i/o standards and benchmarks based on idealized and real, field-scale test cases. A unified reporting standard would not advance knowledge of the benefits and drawback of different models unless a set of standard benchmarks and test cases were agreed upon that would encourage model intercomparison studies. While there are many idealized test cases that are reported in the literature, there is no consensus on a set of standard idealized test cases that test different numerical aspects of coastal models, such as advection schemes, horizontal/vertical gridding, nonhydrostatic solvers, free-surface solvers, etc… The community should also agree upon specific study sites that form standard field-scale benchmarks related to different estuarine or coastal regimes. When possible, grids, bathymetry, boundary conditions and forcing, and computational cost should be standardized to eliminate the impact of subjective user choices in model intercomparison studies. Finally, standard I/O formats would need to be agreed upon to reduce barriers related to testing of new models and encourage application of many models to the benchmark sites. Although there are countless possibilities, the community should form a consensus on benchmarks that are needed and specific sites that form the basis for those benchmarks. As examples, the Columbia River Estuary could be the benchmark for a salt-wedge estuary while San Francisco Bay could be the benchmark for a partially-mixed estuary. A specific hurricane event could be the benchmark for storm-surge models, while a specific coastal region could be the benchmark for nearshore modeling.

The community should set standards for model coupling and nesting approaches. Several presentations at the workshop focused on simulations involving coupled modeling frameworks and nested approaches. The most commonly coupled models are circulation and wave models, such as SWAN + ROMS. Some coastal circulation, wave, and storm surge prediction models are dynamically coupled to atmospheric models to obtain surface wind stresses and heat fluxes, and have shown important improvement in both ocean prediction and storm track/intensity forecasts (Zambon et al., 2014a,b; Nelson and He, 2012). Further accuracy can be achieved through coupling of circulation models with hydrology models that include surface runoff from precipitation. These can be particularly important to predict compound flooding events when heavy rains and the associated runoff significantly increase water levels during strong storm surges (e.g. Silva-Araya et al., 2018; Dresback et al., 2011). In addition to coupling of different modeling frameworks, many applications benefit from the ability to nest higher-resolution grids into coarser grids to study a specific region in more detail. The most commonly employed example of grid nesting in ocean modeling is the ROMS-based AGRIF approach (romsagrif.gforge.inria.fr), which allows for one- or two-way nesting on successively refined grids.

Despite the necessity of model coupling and nesting, each implementation employs its own unique methodology for inter-model communication. For example, some models employ the model coupling toolkit (MCT) or the Earth System Modeling Framework (ESMF), which can handle communication on both serial and parallel implementations and are suitable for two-way coupling. Model downscaling implementations involve either two-way nesting, in which boundary values are exchanged and updated by the "parent" and "child" models, or one-way nesting, in which initial and boundary conditions generated by the "parent" model are written to files that are then treated as input for the "child" model.

A standardized approach to model coupling and nesting would provide several advantages over the existing relatively ad-hoc paradigm. First, a standard approach would provide a framework that could be improved upon to make model coupling more efficient. Researchers could work with one framework and study the advantages and disadvantages of different approaches to help streamline the standard. Second, the standard approach would enable coupling of a wider variety of models from which more model comparisons could be performed to assess the benefits of different models. Finally, standardized model coupling approaches could provide a framework for use in applications that rely heavily on forcing and boundary conditions from different models, such as hydrological and atmospheric forcing including winds and heating.

The community should devise standards for grid development and quality assessment. It would be difficult to develop a grid generation tool that could be applied to general coastal modeling problems given the wide variety of grid types involved. Indeed, there are countless grid generation tools and there is no obvious best choice. Nevertheless, grid generation is largely subjective because of the difficulty in resolving grid-scale coastal and bathymetric features (See Section 3.2.6). While it would be difficult to eliminate this subjectivity, it could largely be reduced if such grid-scale variability were eliminated, either through bathymetric smoothing at subgrid scales or through higher-resolution grids. This may not be appropriate for many applications given the need to include grid-scale coastal variability on some domains, particularly in estuaries with complex island or channel networks. However, given the need to resolve the coastal submesoscale, as discussed in Section 4.3, higher grid resolution would inherently lead to less constraints on grid quality for grid generation tools. In addition to higher resolution, the concept of subgrid bathymetry (Section 3.2.7) also relieves the constraints associated with grid masking or coastline-following grids.

In the shorter term, the community should focus on encouraging more detailed reporting of grid generation strategies, grid quality metrics, and grid sensitivity studies. Grid generation strategies should more faithfully outline choices made regarding grid masking or adjustment, particularly if there was a strategy that could be quantified over one that was subjective. Grid quality metrics should also be reported (e.g. skewness, telescoping fraction, number of masked cells) along with grid sensitivity studies. The overall objective should be to encourage reproducibility of results regardless of the model or grid generation tool, while noting that reproducibility can be affected by factors that cannot be controlled, such as different variable precision among codes (i.e. 32- vs. 64 bit floating-point arithmetic) or stochasticity. More open discussion of the process behind and results of grid generation will hopefully facilitate development of community tools that are robust and not specific to a particular model, such as the Shingle framework (Candy and Pietrzak, 2018).

Validation metrics should be standardized and include dynamically relevant, integrated metrics that are representative of the overall utility of the model. In addition to the skill score of Murphy (1988), as discussed in Section 3.2.2, there are many metrics used to compare coastal model predictions to observations, such as the model skill metric of Wilmott (1981) and standard statistical metrics such as the correlation coefficient and mean and root-mean-square errors. Because there is a general lack of agreement on standards for these metrics, the community should make a concerted effort to create such standards, with the understanding that these will likely be highly site- and problem-specific. For example, the choices and metrics used to evaluate model ability to reproduce SSCs in a salt marsh would be very different from those used to evaluate model ability to reproduce the significant wave heights during a hurricane. Ultimately, details of the validation metrics should be part of the aforementioned standards related to reporting guidelines and benchmarks.

In addition to standardizing existing validation metrics, new validation metrics should be devised that incorporate integrated or dynamical quantities, such as fluxes (area-integrated quantities) or time-averaged or low-frequency metrics. For example, different components of the salt flux (Stokes drift, mean, etc...) might be more appropriate validation metrics than time series of bottom salinity. The challenge with such metrics is that, while they are readily computed from three-dimensional model outputs, it is harder to compute them with observations. Observational campaigns should therefore focus on methods to better validate such integrated quantities in models. Advances in remote-sensing technologies are promising in this regard given their ability to measure spatial distributions of water properties at increasingly higher resolution (See Section 3.3.2). Some integrated metrics do not require observations, such as the ratio of numerical to physical mixing (see Sections 3.2.5 and 3.2.8), for which the ideal model would eliminate the numerical mixing entirely.

4.3. Resolve the coastal submesoscale

The community should collaborate more closely with the high-performance computing and applied mathematics communities to develop high-resolution, accurate models that directly compute the coastal submesoscale. As discussed in Section 3.1.1, it is unlikely that parameterizations for coastal submesoscale processes can be developed given that such processes are highly site-specific and dependent on local geometry and other related physical processes. Therefore, the coastal modeling community should focus on developing modeling tools that can directly simulate such processes in addition to attempting to parameterize them. Simulations at grid resolutions that would resolve the coastal submesoscale would require O(1–10 m) horizontal grid resolution in estuaries and O(0.1–1 km) in coastal shelf domains, which would place a heavy burden on computational requirements. However, high-performance computing platforms have advanced significantly in the past few decades and there is great potential for the development of high-resolution coastal models that run efficiently on such platforms (See Section 3.4). With higher resolution, models would be less susceptible to numerical error which would enable quantification of model uncertainty due to bathymetry and boundary conditions. Less numerical error would also allow for assessment of the benefits of more advanced computational techniques which are traditionally reserved for idealized problems.

4.4. Coordinate observational and modeling studies to improve parameterizations

Parameterizations should be tested and advanced using direct comparison between high-resolution, state-of-the-art measurement technologies and focused modeling studies. There is active research in many areas related to parameterizations of unresolved processes in coastal models (See Section 3.1). The community identified the following as among the most important and relevant for coastal modeling, noting the importance of developing parameterizations that require as little tuning as possible:

(1) Parameterizations of the spatial and temporal variability in horizontal diffusion and dispersion, bottom roughness and unresolved drag, including dependence on both physical (bedform, grain size, vegetation, kelp, corals, waves) and model (grid resolution, advection scheme) characteristics.
(2) Nearshore wave modeling, wave breaking parameterizations, wave-mud damping.
(3) Air–sea interaction under high wind conditions, including air–sea momentum and buoyancy flux exchanges, wave breaking and wave–current interactions.
(4) Sediment transport modeling — erosion parameterizations, flocculation settling, bed consolidation, biological effects.
(5) Morphodynamics.

While there has been extensive work on parameterizations within each of the categories listed, it is not always clear whether the parameterizations improve the coastal models in which they are implemented. Therefore, to be relevant for coastal scale processes, improvements to parameterizations should clearly demonstrate improved predictive capability of coastal models. Development of parameterizations with clear connections to coastal model results requires stronger collaboration between observationalists, experimentalists, and modelers over different scales (i.e. large-scale vs. LES and DNS), and it also requires development and application of more advanced observational techniques. As an example, parameterizations of wind-wave sediment resuspension are difficult to test in the field because of the difficulty in observing the true bed stress and the true near-bed sediment erosion. However, it is now possible to directly measure turbulence, mean flow, and SSCs in 1-mm bins near the bed using the profiling vectrino, which allows for direct assessment of the accuracy of existing parameterizations of bottom drag and sediment erosion (See Section 3.3.1). Such instruments also allow for integration of LES or DNS results into development of improved parameterizations because they can be validated. Recent advances in remote sensing technology also allow for tighter coupling between observations and models since remote sensing provides higher spatial resolution that can be used to test parameterizations (See Section 3.3.2).

4.5. Robust parameter estimation and uncertainty quantification

Coastal models should incorporate advanced tools to more robustly estimate parameters and quantify uncertainty. The greatest impediment to the development of more accurate coastal models is a lack of knowledge of the uncertainty. The uncertainty has numerous sources, including parameterization error, numerical error (including the discretization and errors related to grid quality) and errors from boundary conditions and forcing. The path to reducing the errors related to each of these sources on their own is clear, and many of the recommendations in this paper suggest strategies to reduce those errors. However, owing to an inability to quantify the relative contribution of different sources of uncertainty, accurate coastal modeling relies more on subjective choices (See Section 3.2.5) than it does on quantitative metrics. Subjectivity plays a dominant role in much of coastal modeling given that accurate simulations require an experienced user to make decisions in an ad-hoc manner during the modeling process, including (1) the numerical methods or simply the choice of which coastal model to use, (2) the parameterizations and their underlying constants, (3) choice of suitable datasets for boundary conditions and forcing and the interpolation techniques to impose those conditions at model grid points, (4) the model grid, and (5) validation techniques. The result is that accuracy of model results is typically attributed more to the experience of the model user than to the accuracy of the model itself.

To eliminate the subjectivity related to coastal modeling, the community should incorporate advanced tools in applied mathematics and computer science to quantify uncertainty and develop robust techniques to objectively guide model choices and estimate optimal model parameters. These advanced tools include uncertainty quantification, data assimilation, and machine learning. Data assimilation methods use observations to improve predictions and are well established in regional ocean models (e.g. Edwards et al., 2015), largely owing to the prevalence of regional scales in operational modeling systems that must assimilate data to ensure predictability. Given its success at regional scales, there is ample room for data assimilation in coastal modeling studies, particularly in the context of parameter estimation. Data assimilation methods can inform the optimal parameter sets that minimize the difference between predictions and observations, thus providing a quantitative methodology to estimate parameters that are unknown or difficult to measure. For example, Zhang et al. (2018) assimilated remote-sensing data of surface SSC to estimate the spatial distribution of the settling velocity (which is typically a tunable parameter, as discussed in Section 3.1.4) in a three-dimensional cohesive sediment transport model. Similarly, Zhang et al. (2011) used data assimilation to estimate the spatial distribution of bottom friction coefficients (which are also typically tuned, as discussed in Section 3.2.5) in a regional tidal model. While the focus of data assimilation is to use observations to minimize some measure of the model error, the source of the error is determined with methods in uncertainty quantification, which are also popular in regional ocean modeling (e.g. Lermusiaux et al., 2006). As an example in the coastal ocean, Manderson et al. (2019) quantified the uncertainty of the density stratification and demonstrated how the uncertainty is manifested in nonlinear internal gravity wave models. Given the many tunable parameters in coastal modeling, particularly for sediment transport, it is important to understand the uncertainty related to each parameter to avoid the potential for equifinality, or the possibility of the same result arising from different sets of parameters (van Maren and Cronin, 2016). In addition to providing a robust framework to characterize the numerous sources of uncertainty in coastal models, uncertainty quantification can also help prioritize future research directions based on where uncertainty in coastal models is greatest.

Owing to the continued improvement of observational technologies and increased quantities of observational data (See Section 3.3), more machine learning should be incorporated into coastal ocean modeling. Because machine learning extracts relationships from datasets without the need for models based on first principles, it can be used to estimate parameters that are difficult if not impossible to measure. Machine learning techniques have seen great success as a tool to understand and predict coastal sediment transport and morphodynamics, as discussed in the review article by Goldstein et al. (2019). As examples, Yoon et al. (2013) used an artificial neural network approach to determine the hydrodynamic parameters that best predicted SSC in the surf zone, while Goldstein and Coco (2014) used machine learning to predict the particle settling velocity in a dataset derived from various suspended sediment flows. This approach to determining parameters from data can be combined with models in what are referred to as hybrid models, wherein machine learning is used to determine model parameters based on observational data (Goldstein et al., 2019). Like data assimilation, this hybrid approach appears to be a promising method to reduce ad-hoc tuning and subjective parameter choices in coastal ocean modeling.

5. Conclusions

The primary outcome of the workshop was agreement on the need to reduce subjectivity in implementation of coastal ocean models. This subjectivity arises from the need to make choices that rely on experience rather than quantitative metrics. Ironically, because only experienced model developers and users attend a workshop of this kind, the model results that are presented reflect the subjective choices that can only be made with extensive experience. It was agreed that subjectivity should be reduced through development of a common framework for coastal model users and developers through stronger engagement with applied mathematics and computer science communities, and through implementation of methods in data assimilation, uncertainty quantification, and machine learning to understand the sources of uncertainty and quantify parameter choices in coastal ocean modeling.

A second outcome of the workshop was an understanding of the importance of setting standards for numerous aspects of coastal modeling, the lack of which is partially related to the subjectivity inherent to the current state-of-the-art. Although workshop participants had extensive experience with models, most lamented at the lack of standards to guide model development and dissemination of results. The greatest advantage of setting standards is that they encourage the community to focus efforts in favor of continued model assessment and improvement. It was thus agreed that the community should focus on setting standards for the following aspects of coastal modeling: (1) implementation details needed to reproduce model results, (2) input/output standards for ease of model inter-comparison, (3) benchmarks to test and compare model performance, (4) coupling and model nesting, (5) grid generation, and (6) model validation.

Regarding technical details of coastal models, it was agreed that it is difficult to assess the advantages of different numerical methods or parameterizations. This is due in part to the complexity of coastal modeling and a lack of standards to assess and compare models, and hence can be partially addressed with the outcomes discussed above. However, a basic theme emerged regarding the development of advanced numerical methods and was related to the “coastal submesoscale” throughout the workshop. This refers to horizontal scales that are smaller than the horizontal bathymetric scale but larger than the depth in coastal modeling. Unlike ocean submesoscales, these coastal submesoscales are strongly controlled by the coastal geometry and hence are highly site specific. As a result, there is little hope in developing parameterizations for them, and hence the community should work toward resolving coastal submesoscales with high-resolution simulations. Like the subjectivity problem, this also warrants collaboration with the applied math and computer science communities, but in this case to develop accurate numerical methods and high-resolution, efficient simulations on advanced HPC systems.

While it is possible to resolve the coastal submesoscale, smaller-scale processes with scales smaller than the depth will likely never be resolved. Not only are these scales prohibitively small, but they are dictated by small-scale features that are hard to measure and hence must be modeled or parameterized, such as turbulence. The community should continue to focus on developing parameterizations for such processes, following the wealth of research that has already been done to date. However, it was agreed that there should be tighter coupling between observations, laboratory experiments, and modeling to focus specifically on developing and testing of parameterizations in coastal models. In the past, it has been difficult to test parameterizations in field-scale models because of limitations in observational technologies which could not directly measure the parameters needed for the processes being parameterized (e.g. the bottom stress or sediment erosion rates). Observational technologies have advanced significantly and hence it is now possible to directly test parameterizations in-situ.

Accomplishing the objectives laid out in this paper will require buy-in from funding agencies to support critical components of modeling that have not been part of traditional funding streams in the past. This could include support for research that focuses on inter-comparison studies or development of benchmarks or modeling standards such as I/O, coupling, or validation metrics. Such benchmarks or standards could then be the focus of future workshops on coastal modeling to foster collaboration among different groups within the coastal modeling community. In a similar vein, while model data is typically integrated into proposal data management plans, model test cases and supporting documentation could be an integral part of these plans. Funding agencies should also encourage collaboration between applied mathematicians, computer scientists, and coastal modelers to help accomplish many of the objectives laid out in this paper.

Funding agencies will play an important role in the future of coastal ocean modeling, but buy-in of the objectives laid out in this paper will ultimately come from coastal modeling community members who are tasked with reviewing proposals and recommending funding. Therefore, the proposal submission and review process should involve new priorities and evaluation procedures, and the community needs to identify and develop sustainable means of funding the initiatives proposed in this paper. Given the complexity of developing, testing, and maintaining coastal models, they can be just as difficult and costly to develop and support as ships or state-of-the-art equipment and instrumentation. Therefore, models should be treated as a fundamental component of critical infrastructure needed to support research, just like laboratory facilities, field instrumentation, and research vessels. The notion that models constitute critical infrastructure implies that model maintenance and development should be an important component of infrastructure or facilities sections of proposals. As with ships and major laboratory facilities that are used broadly by the science community, coastal model development, maintenance, and support cannot be expected to be funded only through core science budgets that support hypothesis-driven science. It has often been the case that new models or parameterizations have emerged from such hypothesis-driven research, but this ad-hoc approach is unsustainable as coastal models are now used broadly by non-developers to advance basic science. Coastal models have become an important community asset that should be supported like other key infrastructure, which will likely require commitment and coordination of resources across multiple funding agencies (e.g., the federal agencies in the United States: NSF, NOAA, ONR, DOE, USGS). A key result of this workshop was that the range of coastal model applications benefits from a diversity of modeling approaches, but their accessibility and evaluation are hampered by legacy impediments. Developing the tools and frameworks to lower the structural barriers requires investment in order to realize an improved next generation of coastal ocean models.

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Appendix. Workshop participants and presentation titles

Invited early-career scientists indicated with *. Workshop presentations are available for download from web.stanford.edu/~fringer/nsf-workshop-2018.

Ateljevich, Eli (Cal. Dept of Water Resources): From coast to estuary to channels: Challenges in cross-scale modeling of the San Francisco Bay-Delta

Baptista, Antonio (Oregon Health and Science University): Is in silico estuarine oceanography here yet? Lessons from a humbling benchmark

Blain, Cheryl Ann (Naval Research Laboratory): Approaches to capture freshwater influence in coastal and estuarine waters

Burchard, Hans (Leibniz Institute for Baltic Sea Research): The concept of numerical mixing in coastal oceans

Chai, Fei (U. Maine): Modeling nutrients and plankton dynamics of the San Francisco Bay

Chao, Yi (UCLA): Modeling the California coastal ocean and its interactions with San Francisco Bay

Chen, Changsheng (U. Mass Dartmouth): Importance of Resolving Coastal-Estuarine-Wetland Interactions in Estuarine Modeling

*Davis, Kristen (U. C. Irvine): Spatially-continuous observations of shelf and estuarine processes - what can new observational tools tell us about what we're getting right and wrong in coastal models?

Dawson, Clint (U.T. Austin): Some HPC Challenges in Coastal Modeling

*Dietrich, Casey (NCSU): Connecting Coastal Infrastructure to Predictions of Storm Surge and Flooding

Fringer, Oliver (Stanford): Will we ever simulate, via nonhydrostatic LES, real estuarine and coastal problems?

Ganju, Neil (USGS): Progress and challenges in simulating coupled hydrodynamic-vegetation processes

Georgas, Nickitas (Jupiter): Predicting Risk in a Changing Climate

Geyer, Rocky (WHOI): Estuarine salinity variance and mixing: is numerical diffusion trying to tell us something?

*Giddings, Sarah (Scripps Inst. of Oceanography): Capturing the dynamics of ocean-estuarine exchange when small discharge rivers matter

Gross, Edward (U. C. Davis): Hydrodynamic and particle-tracking modeling to support fish migration studies

He, Ruoying (NCSU): Modeling air-sea interactions during storms

*Hegermiller, Christie (WHOI): Towards simulating extreme coastal morphological change using coupled models

Hetland, Robert (Texas A&M University): The whimsy of model-data comparison in coastal ocean modeling

Hsu, Tom (U. Delaware): Insights into several issues in sediment dynamics investigated by turbulence-scale and wave-scale models

Kirby, Jim (U. Delaware): Surface waves: The interface between phase-resolving and phase-averaged models, and outstanding issues in each setting

*Klingbeil, Knut (Leibniz Institute for Baltic Sea Research): The problem of numerical mixing and its mitigation through adaptive vertical coordinates

*Kumar, Nirnimesh (U. Washington): Parameterizing the effect of surf zone eddies in 3D models: Implications for cross-shore exchange and surf zone dispersion

Li, Ming (U. Maryland): Climate downscaling projections for estuarine hypoxia and acidification using coupled hydrodynamic-biogeochemical models

Luettich, Rick (U. North Carolina): Challenges of moving from hindcasting to forecasting storm surge and inundation

MacCready, Parker (U Washington): Challenges in Realistic Modeling of Estuary-Shelf Connections

*Moriarty, Julia (USGS): Challenges and Opportunities in Regional-Scale Hydrodynamic-Sediment Transport Modeling

*Olabarrieta, Maitane (U. Florida): Modeling the long-term morphodynamic evolution of estuaries: advances and challenges

*Orton, Phillip (Stevens Inst. of Tech.): The utility of fast, accurate models - stories from the front lines of disaster and adaptation

Ozkan-Haller, Tuba (Oregon State U.): Nearshore modeling: What's data got to do with it?

Pietrzak, Julie (T.U. Delft): Lessons learnt from a tidal river plume, the importance of frontal dynamics near the river mouth

Ralston, David (WHOI): Modeling sharp salinity gradients in a tidal salt wedge and river plume

Scully, Malcolm (WHOI): Bathymetrically controlled inflow events in Chesapeake Bay

Shi, Fengyan (U. Delaware): Simulations of river plumes using a sub-meter resolution non-hydrostatic model

*Siedlecki, Samantha (U. Connecticut Marine Sciences): Getting it right for the right reasons- Lessons from simulating regional biogeochemistry as part of decision-support tool development

Signell, Rich (USGS): Interactive, Scalable, Data-Proximate Analysis of Coastal Ocean Model data in the Cloud

*Vitousek, Sean (U. Illinois Chicago): Challenges in modeling waves, turbulence, and sediment transport across scales

Westerink, Joannes (Notre Dame): The Evolution of Process and Scale Coupling in Coastal Ocean Hydrodynamic Modeling

Wilkin, John (Rutgers): The IOOC Task Team on coastal modelling for IOOS: A community consensus on research priorities for integrated analysis across littoral, estuary and shelf regimes

Zhang, Joseph (Virginia Institute of Marine Science): Simulating estuarine circulation in the Chesapeake Bay-Shelf system

References

Adcroft, A., Hallberg, R., 2006. On methods for solving the oceanic equations of motion in generalized vertical coordinates. Ocean Model. 11 (1–2), 224–233.

Adcroft, A., Hill, C., Marshall, J., 1997. Representation of topography by shaved cells in a height coordinate ocean model. Mon. Weather Rev. 125, 2293–2315.

Ainsworth, M., 2004. Dispersive and dissipative behaviour of high order discontinuous Galerkin finite element methods. J. Comput. Phys. 198, 106–130.

Allahdadi, M.N., Gunawan, B., He, R., Neary, V.S., 2019. Development and validation of a regional-scale high-resolution unstructured model for wave energy resource characterization along the US East Coast. Renew. Energy 136, 500–511.

Arakawa, A., Lamb, V.R., 1977. Computational design of the basic dynamical processes of the UCLA general circulation model. Methods Comput. Phys. 17, 173–265.

Ardhuin, F., Rogers, E., Babanin, A.V., Filipot, J.F., Magne, R., Roland, A., et al., 2010. Semiempirical dissipation source functions for ocean waves. Part I: Definition, calibration, and validation. J. Phys. Oceanogr. 40 (9), 1917–1941.

Auclair, F., Benshila, R., Debreu, L., Ducousso, N., Dumas, F., Marchesiello, P., Lemarié, F., 2018. Some recent developments around the CROCO initiative for complex regional to coastal modeling. In: COMOD 2018 - Workshop on Coastal Ocean Modelling, Hambourg, Germany.

Balachandar, S., Eaton, J.K., 2010. Turbulent dispersed multiphase flow. Annu. Rev. Fluid Mech. 42, 111–133.

Bennis, A., Ardhuin, F., Dumas, F., 2011. On the coupling of wave and three-dimensional circulation models: Choice of theoretical framework, practical implementation and adiabatic tests. Ocean Model. 40 (3–4), 260–272.

Bernard, P.-E., Chevaugeon, N., Legat, V., Deleersnijder, E., Remacle, J.-F., 2007. High- order h-adaptive discontinuous Galerkin methods for ocean modelling. Ocean Dynam. 57, 109–121.

Beudin, A., Kalra, T.S., Ganju, N.K., Warner, J.C., 2017. Development of a coupled wave-flow-vegetation interaction model. Comput. Geosci. 100, 76–86.

Bever, A.J., MacWilliams, M.L., 2013. Simulating sediment transport processes in San Pablo Bay using coupled hydrodynamic, wave, and sediment transport models. Mar. Geol. 345, 235–253.

Bleck, R., Boudra, D., 1981. Initial testing of a numerical ocean circulation model using a hybrid (quasi-isopycnic) vertical coordinate. J. Phys. Oceanogr. 11, 755–770.

Blumberg, A.F., Mellor, G.L., 1987. A description of a three-dimensional coastal ocean circulation model. In: Heaps, N. (Ed.), Three-Dimensional Coastal Ocean Models. In: Coastal and Estuarine Sciences, vol. 4, Amer. Geophys. Union, pp. 1–16.

Booij, N., Ris, R.C., Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions, Part I, model description and validation. J. Geophys. Res. C4 (104), 7649–7666.

Branch, R.A., Horner-Devine, A.R., Akan, C., Chickadel, C.C., Farquharson, G., Hudson, A., Talke, S.A., Thompson, J., Jessup, A.T., 2018. Airborne LiDAR measurements and model simulations of tides, waves, and surface slope at the mouth of the Columbia River. IEEE Trans. Geosci. Remote Sens. 56 (12), 7038–7048.

Brand, A., Noss, C., Dinkel, C., Holzner, M., 2016. High-resolution measurements of turbulent flow close to the sediment–water interface using a bistatic acoustic profiler. J. Atmos. Ocean. Technol. 33, 769–788.

Burchard, H., Baumert, H., 1995. On the performance of a mixed layer model based on the k-e turbulence closure. J. Geophys. Res. 100, 8523–8540.

Burchard, H., Beckers, J.-M., 2004. Non-uniform adaptive vertical grids in one-dimensional numerical ocean models. Ocean Model. 6 (1), 51–81.

Burchard, H., Bolding, K., 2002. GETM: A General Estuarine Transport Model, Scientific Documentation. Tech. Rep. EUR 20253 EN. European Commission.

Burchard, H., Bolding, K., Ruiz Villarreal, M., 1999. GOTM – a General Ocean Turbulence Model. Theory, Applications and Test Cases. Tech. Rep. EUR 18745 EN. European Commission.

Burchard, H., Rennau, H., 2008. Comparative quantification of physically and numerically induced mixing in ocean models. Ocean Model. 20 (3), 293–311.

Candy, A.S., 2017. An implicit wetting and drying approach for non-hydrostatic baroclinic flows in high aspect ratio domains. Adv. Water Resour. 102, 188–205.

Candy, A.S., Pietrzak, J.D., 2018. Shingle 2.0: Generalising self-consistent and automated domain discretisation for multi-scale geophysical models. Geosci. Model Dev. 11 (213).

Cantero, M.I., Balachandar, S., Cantelli, A., Pirmez, C., Parker, G., 2009a. Turbidity current with a roof: direct numerical simulation of self-stratified turbulent channel flow driven by suspended sediment. J. Geophys. Res. Oceans 114, C03008.

Cantero, M.I., Balachandar, S., Parker, G., 2009b. Direct numerical simulation of stratification effects in a sediment-laden turbulent channel flow. J. Turbul. 10, 27.

Casulli, V., 1999. A semi-implicit finite difference method for nonhydrostatic free surface flows. Internat. J. Numer. Methods Fluids 30, 425–440.

Casulli, V., 2009. A high–resolution wetting and drying algorithm for free–surface hydrodynamics. Internat. J. Numer. Methods Fluids 60, 391–408.

Casulli, V., Cattani, E., 1994. Stability, accuracy and efficiency of a semi-implicit method for three-dimensional shallow water flow. Comput. Math. Appl. 27 (4), 99–112.

Casulli, V., Stelling, G.S., 2010. Semi-implicit subgrid modelling of three-dimensional free-surface flows. Internat. J. Numer. Methods Fluids 67, 441–449.

Casulli, V., Zanolli, P., 2002. Semi-implicit numerical modelling of non-hydrostatic free-surface flows for environmental problems. Math. Comput. Model. 36 (9–10), 1131–1149.

Casulli, V., Zanolli, P., 2005. High resolution methods for multidimensional advection-diffusion problems in free-surface hydrodynamics. Ocean. Model. 10 (1–2), 137–151.

Chai, F., Dugdale, R.C., Peng, T.H., Wilkerson, F.P., Barber, R.T., 2002. One-dimensional ecosystem model of the equatorial Pacific upwelling system. Part I: model development and silicon and nitrogen cycle. Deep-Sea Res. II 49 (13–14), 2713–2745.

Chai, F., Jiang, M.S., Barber, R.T., Dugdale, R.C., Chao, Y., 2003. Interdecadal variation of the transition zone chlorophyll front: A physical-biological model simulation between 1960 and 1990. J. Oceanogr. 59 (4), 461–475.

Chai, F., Jiang, M.S., Chao, Y., Dugdale, R.C., Chavez, F., Barber, R.T., 2007. Modeling responses of diatom productivity and biogenic silica export to iron enrichment in the equatorial Pacific Ocean. Global Biogeochem. Cy. 21, GB3S90.

Chang, S., Iaccarino, G., Ham, F., Elkins, C., Monismith, S., 2014. Local shear and mass transfer on individual coral colonies: Computations in unidirectional and wave-driven flows. J. Geophys. Res. Ocean. 119, 2599–2619.

Chao, Y., Farrara, J.D., Zhang, H., Armenta, K.J., Centurioni, L., Chavez, F., Girton, J.B., Rudnick, D., Walter, R.K., 2018. Development, implementation, and validation of a California coastal ocean modeling, data assimilation, and forecasting system. Deep-Sea Res. II 151, 49–63.

Chao, Y., Farrara, J.D., Zhang, H., Zhang, Y.J., Ateljevich, E., Chai, F., Davis, C.O., Dugdale, R., Wilkerson, F., 2017b. Development, implementation, and validation of a modeling system for the San Francisco Bay and Estuary. Estuar. Coast. Shelf Sci. 194, 40–56.

Chao, Y., Li, Z., Farrara, J., McWilliams, J.C., Bellingham, J., Capet, X., Chavez, F., Choi, J.-K., Davis, R., Doyle, J., Frantaoni, D., Li, P.P., Marchesiello, P., Moline, M.A., Paduan, J., Ramp, S., 2009. Development, implementation and evaluation of a data-assimilative ocean forecasting system off the central California coast. Deep-Sea Res. II 56, 100–126.

Chen, C., Liu, H., Beardsley, R.C., 2003. An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: Application to coastal ocean and estuaries. J. Atmos. Ocean. Technol. 20, 159–186.

Cheng, Z., Yu, X., Hsu, T.-J., Ozdemir, C.E., Balachandar, S., 2015. On the transport modes of fine sediment in the wave boundary layer due to resuspension/deposition: a turbulence-resolving numerical investigation. J. Geophys. Res.-Oceans 120, 1918–1936.

Chou, Y.J., Fringer, O.B., 2008. Modeling dilute sediment suspension using LES with a dynamic mixed model. Phys. Fluids 20, 115103.

Chou, Y.-J., Fringer, O.B., 2010. A model for the simulation of coupled flow-bed form evolution in turbulent flows. J. Geophys. Res.-Oceans 115, C10041.

Chou, Y.-J., Holleman, R.C., Fringer, O.B., Stacey, M.T., Monismith, S.G., Koseff, J.R., 2015. Three-dimensional wave-coupled hydrodynamics modeling in South San Francisco Bay. Comput. Geosci. 85, 10–21.

Chou, Y.-J., Nelson, K.S., Holleman, R.C., Fringer, O.B., Stacey, M.T., Lacy, J.R., Monismith, S.G., Koseff, J.R., 2018. Three-dimensional modeling of fine sediment transport by waves and currents in a shallow estuary. J. Geophys. Res. Ocean. 123, http://dx.doi.org/10.1029/2017JC013064.

Chow, F.K., Street, R., Xue, M., Ferziger, J.H., 2005. Explicit filtering and resconstruction turbulence modeling for large-eddy simulation of neutral boundary layer flow. J. Atmos. Sci. 62, 2058–2077.

Chua, V., Fringer, O.B., 2011. Sensitivity analysis of three-dimensional salinity simulations in North San Francisco Bay using the unstructured-grid SUNTANS model. Ocean Model. 39 (3–4), 332–350.

Cloern, J.E., 1987. Turbidity as a control on phytoplankton biomass and productivity in estuaries. Cont. Shelf Res. 7 (11–12), 1367–1381.

Constantinescu, G., Koken, M., Zeng, J., 2011a. The structure of turbulent flow in an open channel bend of strong curvature with deformed bed: Insight provided by an eddy resolving numerical simulation. Water Resour. Res. 47, W05515.

Constantinescu, G., Miyawaki, S., Rhoads, B., Sukhodolov, A., Kirkil, G., 2011b. Structure of turbulent flow at a river confluence with momentum and velocity ratios close to 1: Insights from an eddy-resolving numerical simulation. Water Resour. Res. 47, W05507.

Danilov, S., 2013. Ocean modeling on unstructured meshes. Ocean Model. 69, 195–210.

Delandmeter, P., Lambrechts, J., Legat, V., Vallaeys, V., Naithani, J., Thiery, W., Remacle, J.-F., Deleersnijder, E., 2018. A fully consistent and conservative vertically adaptive coordinate system for SLIM 3D v0.4 with an application to the thermocline oscillations of Lake Tanganyika. Geosci. Model Dev. 11, 1161–1179.

Delandmeter, P., Lewis, S., Lambrechts, J., Deleersnijder, E., Legat, V., Wolanski, E., 2015. The transport and fate of riverine fine sediment exported to a semi-open system. Estuar. Coast. Shelf Sci. 167, 336–346.

Delft3D-Flow, 2019. Delft3D-Flow: Simulation of Multi-Dimensional Hydrodynamic Flows and Transport Phenomena, Including Sediments. User Manual. Version 3.15., Deltares, Delft, The Netherlands. https://content.oss.deltares.nl/delft3d/manuals/Delft3D-FLOW_User_Manual.pdf.

Dietrich, J., 2017. Bathymetric structure from motion: Extracting shallow stream bathymetry from multi-view stereo photogrammetry. Earth Surf. Process. Landf. 42, 355–364.

Dresback, K.M., Fleming, J.G., Blanton, B.O., Kaiser, C., Gourley, J.J., Tromble, E.M., Luettich, R.A., Kolar, R.L., Hong, Y., van Cooten, S., Vergara, H.J., Flamig, Z.L., Lander, H.M., Kelleher, K.E., Nemunaitis-Monroe, K.L., 2013. Skill assessment of a real-time forecast system utilizing a coupled hydrologic and coastal hydrodynamic model during Hurricane Irene (2011). Cont. Shelf Res. 71. 78–94.

Edwards, C.A., Moore, A.M., Hoteit, I., Cornuelle, B.D., 2015. Regional ocean data assimilation. Annu. Rev. Mar. Sci. 7, 21–42.
Egan, G., Cowherd, M., Fringer, O., Monismith, S., 2019. Observations of near-bed shear stress in a shallow, wave- and current-driven flow. J. Geophys. Res.-Oceans 124, http://dx.doi.org/10.1029/2019JC015165.k.
Erikson, L.H., Wright, S.A., Elias, E., Hanes, D.M., Schoellhamer, D.H., Largier, J., 2013. The use of modeling and suspended sediment concentration measurements for quantifying net suspended sediment transport through a large tidally dominated inlet. Mar. Geol. 345, 96–112.
Feddersen, F., Clark, D.B., Guza, R.T., 2011. Modeling of surfzone tracer plumes: 1. Waves, mean currents, and low-frequency eddies. J. Geophys. Res. 116, C11027.
Fong, D., Monismith, S., Stacey, M., Burau, J., 2009. Turbulent stresses and secondary currents in a tidal-forced channel with significant curvature and asymmetric bed forms. J. Hydraul. Eng. 135 (198).
Ford, R., Pain, C.C., Piggott, M.D., Goddard, A.J.H., de Oliveira, C.R.E., Umpleby, A.P., 2004. A nonhydrostatic finite-element model for three-dimensional stratified oceanic flows. Mon. Weather Rev. 132, 2816–2844.
Fringer, O.B., Gerritsen, M., Street, R.L., 2006. An unstructured-grid, finite-volume, nonhydrostatic, parallel coastal ocean simulator. Ocean Model. 14 (3–4), 139–173.
Geuzaine, C., Remacle, J.-F., 2009. Gmsh: a 3-D finite element mesh generator with built- in pre- and post-processing facilities. Internat. J. Numer. Methods Engrg. 79, 1309–1331.
Geyer, W.R., Lavery, A.C., Scully, M.E., Trowbridge, J.H., 2010. Mixing by shear instability at high Reynolds number. Geophys. Res. Lett. 37 (L22607).
Geyer, W.R., Traykovski, P., Lavery, A., 2013. The impact of acoustic oceanographic methods on estuarine dynamics research. Proc. Mtgs. Acoust. 19, 005001.
Giddings, S.N., Fong, D.A., Monismith, S.G., Chickadel, C.C., Edwards, K.A., Plant, W.J., Wang, B., Fringer, O.B., Horner-Devine, A.R., Jessup, A.T., 2012. Frontogenesis and frontal progression of a trapping-generated estuarine convergence front and its influence on mixing and stratification. Estuar. Coast. 35 (2), 665–681.
Giraldo, F., Restelli, M., 2008. A study of spectral element and discontinuous Galerkin methods for the Navier–Stokes equations in nonhydrostatic mesoscale atmospheric modeling: Equation sets and test cases. J. Comput. Phys. 227, 3849–3877.
Giraldo, F., Restelli, M., Läuter, M., 2010. Semi-implicit formulations of the Navier–Stokes equations: Application to nonhydrostatic atmospheric modeling. SIAM J. Sci. Comput. 32, 3394–3425.
Glenn, S.M., Grant, W.D., 1987. A suspended sediment stratification correction for combined wave and current flows. J. Geophys. Res. Ocean. 92 (C8), 8244–8264.
Gochis, D.J., Barlage, M., Dugger, A., FitzGerald, K., Karsten, L., McCreight, J., Mills, J., RafieeiNasab, A., Read, L., Sampson, K., Yates, D., Yu, W., 2018. The WRF-Hydro Modeling System Technical Description, (Version 5.0). NCAR Technical Note, 107 pages.
Goldstein, E.B., Coco, G., 2014. A machine learning approach for the prediction of settling velocity. Water Resour. Res. 50 (4), 3595–3601.
Goldstein, E.B., Coco, G., Plant, N.G., 2019. A review of machine learning applications to coastal sediment transport and morphodynamics. Earth-Sci. Rev. 194, 97–108.
Grant, W.D., Madsen, O.S., 1979. Combined wave and current interaction with a rough bottom. J. Geophys. Res. Ocean. 84 (C4), 1797–1808.
Grasso, F., Verney, R., Le Hir, P., Thouvenin, B., Schulz, E., Kervella, Y., Khojasteh Pour Fard, I., Lemoine, J.-P., Dumas, F., Garnier, V., 2018. Suspended sediment dynamics in the macrotidal Seine Estuary (France): 1. Numerical modeling of turbidity maximum dynamics. J. Geophys. Res. Ocean. 123 (1), 558–577.
Gräwe, U., Holtermann, P., Klingbeil, K., Burchard, H., 2015. Advantages of vertically adaptive coordinates in numerical models of stratified shelf seas. Ocean Model. 92, 56–68.
Gregg, M.C., D'Asaro, E.A., Riley, J.J., Kunze, E., 2018. Mixing efficiency in the ocean. Annu. Rev. Mar. Sci. 10 (1), 443–473.
Gross, E.S., MacWilliams, M.L., Kimmerer, W.J., 2009. Three-dimensional modeling of tidal hydrodynamics in the San Francisco Estuary. San Francisco Estuary Watershed Sci. 7 (2).
Guerin, T., Bertin, X., Coulombier, T., de Bakker, A., 2018. Impacts of wave-induced circulation in the surf zone on wave setup. Ocean Model. 123, 86–97.
Guerin, T., Bertin, X., Dodet, G., 2016. A numerical scheme for coastal morphodynamic modelling on unstructured grids. Ocean Model. 104, 45–53.
Hally-Rosendahl, K., Feddersen, F., Guza, R.T., 2014. Cross-shore tracer exchange between the surfzone and inner-shelf. J. Geophys. Res. Ocean. 119, 4367–4388.
Hofmeister, R., Burchard, H., Beckers, J.-M., 2010. Non-uniform adaptive vertical grids for 3D numerical ocean models. Ocean Model. 33, 70–86.
Holleman, R., Fringer, O.B., Stacey, M.T., 2013. Numerical diffusion for flow-aligned unstructured grids with application to estuarine modeling. Internat. J. Numer. Methods Fluids 72, 1117–1145.
Horner-Devine, A.R., Chickadel, C.C., 2017. Lobe-cleft instability in the buoyant gravity current generated by estuarine outflow. Geophys. Res. Lett. 44, 5001–5007.
Howard, L., 1961. Note on a paper of John W. Miles. J. Fluid Mech. 10, 509–512.
Ivey, G.N., Winters, K.B., Koseff, J.R., 2018. Density stratification, turbulence, but how much mixing? Annu. Rev. Fluid Mech. 40, 169–184.
Jones, W.P., Launder, B.E., 1972. The prediction of laminarization with a two-equation model of turbulence. Int. J. Heat Mass Transfer 15, 301–314.
Kanarska, Y., Shchepetkin, A., McWilliams, J.C., 2007. Algorithm for nonhydrostatic dynamics in the regional oceanic modeling system. Ocean Model. 18, 143–174.
van Kessel, T., Vanlede, J., de Kok, J., 2011. Development of a mud transport model for the Scheldt Estuary. Cont. Shelf Res. 31, S165–S181.
Kirby, J., 2017. Recent advances in nearshore wave, circulation, and sediment transport modeling. J. Mar. Res. 75 (3), 263–300.
Klingbeil, K., Burchard, H., 2013. Implementation of a direct nonhydrostatic pressure gradient discretisation into a layered ocean model. Ocean Model. 65, 64–77.
Klingbeil, K., Lemarié, F., Debreu, L., Burchard, H., 2018. The numerics of hydrostatic structured-grid coastal ocean models: State of the art and future perspectives. Ocean Model. 125, 80–105.
Klingbeil, K., Mohammadi-Aragh, M., Gräwe, U., Burchard, H., 2014. Quantification of spurious dissipation and mixing – Discrete variance decay in a finite-volume framework. Ocean Model. 81, 49–64.
Komen, G.J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., Janssen, P.A.E.M., 1994. Dynamics and Modelling of Ocean Waves. Cambridge University Press, Cambridge.
Korn, P., Danilov, S., 2017. Elementary dispersion analysis of some mimetic discretizations on triangular C-grids. J. Comput. Phys. 330, 156–172.
Kranck, K., Milligan, T., 1980. Macroflocs: production of marine snow in the laboratory. Mar. Ecol. Prog. Ser. 3, 19–24.
Kumar, N., Feddersen, F., 2016. The effect of Stokes drift and transient rip currents on the inner shelf. Part I: No stratification. J. Phys. Oceanogr. 47, 227–241.
Kumar, N., Feddersen, F., 2017. The effect of Stokes drift and transient rip currents on the inner shelf. Part II: With stratification. J. Phys. Oceanogr. 47, 243–260.
Kumar, N., Voulgaris, G., Warner, J.C., 2011. Implementation and modification of a three-dimensional radiation stress formulation for surf zone and rip-current applications. Coastal Eng. 58, 1097–1117.
Kumar, N., Voulgaris, G., Warner, J.C., Olabarrieta, M., 2012. Implementation of the vortex force formalism in the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system for inner shelf and surf zone applications. Ocean Model. 47, 65–95.
Lai, Z., Chen, C., Cowles, G.W., Beardsley, R.C., 2010a. A nonhydrostatic version of FVCOM: 1. Validation experiments. J. Geophys. Res. 115, C11010.
Lai, Z., Chen, C., Cowles, G.W., Beardsley, R.C., 2010b. A nonhydrostatic version of FVCOM: 2. Mechanistic study of tidally generated nonlinear internal waves in Massachusetts Bay. J. Geophys. Res. 115, C12049.
Lambrechts, J., Hanert, E., Deleersnijder, E., Bernard, P.-E., Legat, V., Remacle, J.-F., Remacle, E., Wolanksi, E., 2008. A multi-scale model of the hydrodynamics of the whole Great Barrier Reef. Estuar. Coast. Shelf Sci. 79 (1), 143–151.
Launder, B.E., Sharma, B.I., 1974. Application of the energy dissipation model of turbulence to the calculation of flow near a spinning disc. Lett. Heat Mass Transfer 1 (2), 131–138.
Lazure, P., Dumas, F., 2008. An external–internal mode coupling for a 3D hydrodynamical model for applications at regional scale (MARS). Adv. Water Resour. 31, 233–250.
Le Roux, D.Y., Rostan, V., Pouliot, B., 2007. Analysis of numerically induced oscillations in 2D finite-element shallow-water models Part I: Inertial-gravity waves. SIAM J. Sci. Comput. 29 (1), 331–360.
Legg, S., Hallberg, R.W., Girton, J.B., 2006. Comparison of entrainment in overflows simulated by z-coordinate, isopycnal and non-hydrostatic models. Ocean Model. 11 (1–2), 69–97.
Legrand, S., Deleersnijder, E., Hanert, E., Legat, V., Wolanski, E., 2006. High-resolution, unstructured meshes for hydrodynamic models of the Great Barrier Reef, Australia. Estuar. Coast. Shelf Sci. 68 (1–2), 36–46.
Lermusiaux, P.F.J., Chiu, C.S., Gawarkiewicz, G.G., Abbot, P., Robinson, A.R., Miller, R.N., Haley, P.J., Leslie, W.G., Majumdar, S.J., Pang, A., Lekien, F., 2006. Quantifying uncertainties in ocean predictions. Oceanography 19 (1), 92–105, Special issue on "Advances in Computational Oceanography", T. Paluszkiewicz and S. Harper (Office of Naval Research) Eds.
Lesser, G.R., Roelvink, J.A., van Kester, J.A.T.M., Stelling, G.S., 2004. Development and validation of a three-dimensional morphological model. Coastal Eng. 51, 883–915.
van Leussen, W., 1994. Estuarine Macroflocs and their Role in Fine-Grained Sediment Transport (Ph.D. thesis). University of Utrecht, Utrecht, The Netherlands.
Lick, W., 2009. Sediment and Contaminant Transport in Surface Waters. CRC Press, Taylor and Francis Publishing, Boca Raton, FL, 400 pp.
Lick, W., Lick, J., Ziegler, C.K., 1992. Flocculation and its effect on the vertical transport of fine-grained sediments. Hydrobiologia 235/236, 1–16.
Lowe, R.J., Koseff, J.R., Monismith, S.G., 2005a. Oscillatory flow through submerged canopies: 1. Velocity structure. J. Geophys. Res. 110, C10016.
Lowe, R.J., Koseff, J.R., Monismith, S.G., Falter, J.L., 2005b. Oscillatory flow through submerged canopies: 2. Canopy mass transfer. J. Geophys. Res. 110, C10017.
Luettich, Jr., R.A., Westerink, J.J., Scheffner, N.W., 1992. ADCIRC: an Advanced Three-Dimensional Circulation Model for Shelves Coasts and Estuaries. Report 1: Theory and methodology of ADCIRC-2DDI and ADCIRC-3DL, Dredging Research Program Technical Report DRP-92-6, U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS, 137 pp.
Luhar, M., Coutu, S., Infantes, E., Fox, S., Nepf, H.M., 2010. Wave-induced velocities inside a model seagrass bed. J. Geophys. Res. 115 (C12005).
Luhar, M., Nepf, H.M., 2011. Flow-induced reconfiguration of buoyant and flexible aquatic vegetation. Limnol. Oceanogr. 56 (6), 2003–2017.
Luhar, M., Nepf, H.M., 2013. From the blade scale to the reach scale: A characterization of aquatic vegetative drag. Adv. Water Resour. 51, 305–316.

Ma, G., Shi, F., Kirby, J.T., 2012. Shock-capturing non-hydrostatic model for fully dispersive surface wave processes. Ocean Model. 43-44, 22–35.

MacWilliams, M.L., Bever, A.J., Gross, E.S., Ketefian, G.S., Kimmerer, W.J., 2015. Three-dimensional modeling of hydrodynamics and salinity in the San Francisco Estuary: An evaluation of model accuracy, X2, and the low–salinity zone. San Francisco Estuary Watershed Sci. 13 (1).

MacWilliams, M., Bever, Foresman, E., 2016. 3-D simulations of the san francisco estuary with subgrid bathymetry to explore long-term trends in salinity distribution and fish abundance. San Francisco Estuary Watershed Sci. 14 (2).

Manderson, A., Rayson, M.D., Cripps, E., Girolami, M., Gosling, J.P., Hodkiewicz, M., Ivey, G.N., Jones, N.L., 2019. Uncertainty quantification of density and stratification estimates with implications for predicting ocean dynamics. J. Atmos. Ocean. Technol. 36, 1313–1330.

van Maren, D.S., Cronin, K., 2016. Uncertainty in complex three-dimensional sediment transport models: equifinality in a model application of the Ems Estuary, the Netherlands. Ocean Dyn. 66 (12), 1665–1679.

Marmorino, G.O., Smith, G.B., Miller, W.D., 2013. Infrared remote sensing of surf-zone eddies. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 6, 1710–1718.

Marshall, J., Adcroft, A., Hill, C., Perelman, L., Heisey, C., 1997a. A finite volume, incompressible Navier–Stokes model for studies of the ocean on parallel computers. J. Geophys. Res. 102 (C3), 5753–5766.

Marshall, J., Hill, C., Perelman, L., Adcroft, A., 1997b. Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling. J. Geophys. Res. 102 (C3), 5733–5752.

Martyr-Koller, R.C., Kernkamp, H.W.J., van Dam, A., van der Wegen, M., Lucas, L.V., Knowles, N., Fregoso, T.A., 2017. Application of an unstructured 3D finite volume numerical model to flows and salinity dynamics in the San Francisco Bay-Delta. Estuar. Coast. Shelf Sci. 192, 86–107.

Masunaga, E., Arthur, R.S., Fringer, O.B., Yamazaki, H., 2017. Sediment resuspension and the generation of intermediate nepheloid layers by shoaling internal bores. J. Mar. Syst. 170, 31–41.

McNeil, J., Taylor, C., Lick, W., 1996. Measurements of erosion of undisturbed bottom sediments with depth. J. Hydr. Engr. 122, 316–324.

McWilliams, J.C., 2016. Submesoscale currents in the ocean. Proc. R. Soc. Lond. Ser. A Math. Phys. Eng. Sci. 472, 20160117.

McWilliams, J.C., Restrepo, J.M., Lane, E.M., 2004. An asymptotic theory for the interaction of waves and currents in coastal waters. J. Fluid Mech. 511, 135–178.

Medeiros, S.C., Hagen, S.C., 2013. Review of wetting and drying algorithms for numerical tidal flow models. Internat. J. Numer. Methods Fluids 71, 473–487.

Mellor, G., 2002. Oscillatory bottom boundary layers. J. Phys. Oceanogr. 32 (11), 3075–3088.

Mellor, G.L., Yamada, T., 1982. Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys. 20, 851–875.

Mendez, F.M., Losada, I.J., 2004. An empirical model to estimate the propagation of random breaking and nonbreaking waves over vegetation fields. Coastal Eng. 51, 103–118.

Mengual, B., Le Hir, P., Cayocca, F., Garlan, T., 2017. Modelling fine sediment dynamics: Towards a common erosion law for fine sand, mud and mixtures. Water 9, 564.

Meyer-Peter, E., Müeller, R., 1948. Formulas for bed-load transport. In: Proceedings of the 2nd Meeting of the International Association for Hydraulic Structures Research, pp. 39–64.

Mietta, F., Chassagne, C., Manning, A.J., Winterwerp, J.C., 2009. Influence of shear rate, organic matter content, pH and salinity on mud flocculation. Ocean Dynam. 59 (5), 751–763.

Miles, J., 1961. On the stability of heterogeneous shear flows. J. Fluid Mech. 10, 496–508.

Monismith, S.G., 2007. Hydrodynamics of coral reefs. Annu. Rev. Fluid Mech. 39 (1), 37–55.

Monismith, S.G., Koseff, J.R., White, B.L., 2018. Mixing efficiency in the presence of stratification: When is it constant? Geophys. Res. Lett. 45, 5627–5634.

Murphy, A.H., 1988. Skill score based on the mean square error and their relationship to the correlation coefficient. Mon. Weather Rev. 116, 2417–2424.

Nelson, K.S., Fringer, O.B., 2018. Sediment dynamics in windwave dominated shallow water environments. J. Geophys. Res.-Oceans 123, 6996–7015.

Nelson, J., He, R., 2012. Effect of the Gulf stream on winter extratropical cyclone outbreaks. Atmos. Sci. Lett. 13, 311–316.

Nepf, H.M., 2012. Flow and transport in regions with aquatic vegetation. Annu. Rev. Fluid Mech. 44, 123–142.

Neveu, E., Moore, A.M., Edwards, C.A., Fiechter, J., Drake, P., Crawford, W.J., Jacox, M.G., Nuss, E., 2016. An historical analysis of the California Current circulation using ROMS 4D-Var: System configuration and diagnostics. Ocean Model. 99, 133–151.

Olabarrieta, M., Geyer, W.R., Coco, G., Friedrichs, C.T., Cao, Z., 2018. Effects of density-driven flows on the long-term morphodynamic evolution of funnel-shaped estuaries. J. Geophys. Res.-Earth 123 (11), 2901–2924.

Olabarrieta, M., Warner, J., Armstrong, B., Zambon, J., He, R., 2012. Ocean-atmosphere dynamics during Hurricane Ida and Nor'Ida: An application of the coupled ocean-atmosphere-wave-sediment transport (COAWST) modeling system. Ocean Model. 43–44, 112–137.

Ozdemir, C.E., Hsu, T.-J., Balachandar, S., 2010. A numerical investigation of fine particle laden flow in an oscillatory channel: the role of particle-induced density stratification. J. Fluid Mech. 665, 1–45.

Pain, C.C., Piggott, M.D., Goddard, A.J.H., Gorman, G.J., Marshall, D.P., Eaton, M.D., Power, P.W., de Oliveira, C.R.E., 2005. Three-dimensional unstructured mesh ocean modelling. Ocean Model. 10 (1–2), 5–33.

Pearson, B., Fox-Kemper, B., Bachman, S.D., Bryan, F.O., 2017. Evaluation of scale-aware subgrid mesoscale eddy models in a global eddy-rich model. Ocean Model. 115, 42–58.

Piggott, M.D., Pain, C.C., Gorman, G.J., Power, P.W., Goddard, A.J.H., 2005. h, r, and hr adaptivity with applications in numerical ocean modelling. Ocean Model. 10, 95–113.

Piomelli, U., Balaras, E., 2002. Wall-layer models for large-eddy simulations. Annu. Rev. Fluid Mech. 34 (1), 349–374.

Platzek, F.W., Stelling, G.S., Jankowski, J.A., Pietrzak, J.D., 2014. Accurate vertical profiles of turbulent flow in z-layer models. Water Resour. Res. 50, 2191–2211.

Pope, S.B., 2000. Turbulent Flows. Cambridge University Press.

Qi, J., Chen, C., Beardsley, R.C., Perrie, W., Cowles, G.R., Lai, Z., 2009. An unstructured-grid finite-volume surface wave model (FVCOM-SWAVE): implementation, validations and applications. Ocean Modell. 28, 153–166.

Ralston, D.K., Cowles, G.W., Geyer, W.R., Holleman, R.C., 2017. Turbulent and numerical mixing in a salt wedge estuary: Dependence on grid resolution, bottom roughness, and turbulence closure. J. Geophys. Res. Ocean. 122, 692–712.

Ralston, D.K., Geyer, W.R., Traykovski, P.A., Nidzieko, N.J., 2013. Effects of estuarine and fluvial processes on sediment transport over deltaic tidal flats. Cont. Shelf Res. 60, S40–S57.

Rao, Y.R., Murthy, C.R., Sinha, P.C., 2008. The coastal ocean. In: Murthy, C.R., Sinha, P.C., Rao, Y.R. (Eds.), Modelling and Monitoring of Coastal Marine Processes. Springer (Dordrecht) & Capital Publishing Company (New Delhi), pp. 3–10.

Reid, E.C., DeCarlo, T.M., Cohen, A.L., Wong, G.T., Lentz, S.J., Safaie, A., Hall, A., Davis, K.A., 2019. Internal waves influence the thermal and nutrient environment on a shallow coral reef. Limnol. Oceanogr. http://dx.doi.org/10.1002/lno.11162.

Reidenbach, M.A., Koseff, J.R., Monismith, S.G., Steinbuck, J.V., Genin, A., 2006. The effects of waves and morphology on mass transfer within branched reef corals. Limnol. Oceanogr. 51 (2), 1134–1141.

van Rijn, L.C., 1993. Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas. Aqua Publications, The Netherlands.

Ringler, T.D., Thuburn, J., Klemp, J.B., Skamarock, W.C., 2010. A unified approach to energy conservation and potential vorticity dynamics for arbitrarily-structured C-grids. J. Comput. Phys. 229, 3065–3090.

Roberts, K.D., Dietrich, J.C., Wirasaet, D., Westerink, J.J., Pringle, W., 2019. Dynamic Load Balancing for Predictions of Storm Surge and Coastal Flooding (in preparation).

Rodi, W., 1984. Turbulence Models and their Application in Hydraulics. A State of the Art Review. Technical Report. Int. Assoc. for Hydraul. Res., Delft, The Netherlands.

Rodi, W., Constantinescu, G., Stoesser, T., 2013. Large-Eddy Simulation in Hydraulics. CRC Press.

Roelvink, J.A., 2006. Coastal morphodynamic evolution techniques. Coast. Eng. 53 (2–3), 277–287.

Rogers, J.S., Monismith, S.G., Fringer, O.B., Koweek, D.A., Dunbar, R.B., 2017. A coupled wave-hydrodynamic model of an atoll with high friction: Mechanisms for flow, connectivity, and ecological implications. Ocean Model. 110, 66–82.

Rohr, J.J., Itsweire, E.C., Helland, K.N., Van Atta, C.W., 1988. Growth and decay of turbulence in a stably stratified shear flow. J. Fluid Mech. 195, 77–111.

Roland, A., Zhang, Y.J., Wang, H.V., Meng, Y., Teng, Y.-C., Maderich, V., Brovchenko, I., Dutour-Sikiric, M., Zanke, U., 2012. A fully coupled 3D wave–current interaction model on unstructured grids. J. Geophys. Res. 117 (C00J33).

Romero, L., Siegel, D.A., McWilliams, J.C., Uchiyama, Y., Jones, C., 2016. Characterizing storm water dispersion and dilution from small coastal streams. J. Geophys. Res. Ocean. 121, 3926–3943.

Rosman, J.H., Denny, M.W., Zeller, R.B., Monismith, S.G., Koseff, J.R., 2013. Interaction of waves and currents with kelp forests (*Macrocystis pyrifera*): Insights from a dynamically scaled laboratory model. Limnol. Oceanogr. 58 (3), 790–802.

Rosman, J.H., Monismith, S.G., Denny, M.W., Koseff, J.R., 2010. Currents and turbulence within a kelp forest (*Macrocystis pyrifera*): Insights from a dynamically scaled laboratory model. Limnol. Oceanogr. 55.

Saffman, P.G., 1970. A model for inhomogeneous turbulent flow. Proc. R. Soc. A 317, 417–433.

Sanford, L.P., 2008. Modeling a dynamically varying mixed sediment bed with erosion, deposition, bioturbation, consolidation, and armoring. Comput. Geosci. 34, 1263–1283.

Sanford, L.P., Maa, J.P.Y., 2001. A unified erosion formulation for fine sediments. Mar. Geol. 179 (1–2), 9–23.

Santilli, E., Scotti, A., 2011. An efficient method for solving highly anisotropic elliptic equations. J. Comput. Phys. 230, 8342–8359.

Scotti, A., Meneveau, C., Lilly, D.K., 1993. Generalized smagorinsky model for anisotropic grids. Phys. Fluids A 5, 2306–2308.

van Sebille, E., Griffies, S.M., Abernathey, R., Adams, T.P., Berloff, P., Biastoch, A., Blanke, B., Chassignet, E.P., Cheng, Y., Colin, J.C., Deleersnijder, E., Döös, K., Drake, H.F., Drijfhout, S., Gary, S.F., Heemink, A.W., Kjellsson, J., Koszalka, I.M., Lange, M., Lique, C., MacGilchrist, G.A., Marsh, R., Mayorga Adame, C.G., McAdam, R., Nencioli, F., Paris, C.B., Piggott, M.D., Polton, J.A., Rühs, S., Shah, S.H.A.M., Thomas, M.D., Wang, J., Wolfram, P.J., Zanna, L., Zika, J.D., 2018. Lagrangian ocean analysis: fundamentals and practices. Ocean Model. 121, 49–75.
Sehili, A., Lang, G., Lippert, C., 2014. High-resolution subgrid models: background, grid generation, and implementation. Ocean Dyn. 64 (4), 519–535.
Seny, B., Lambrechts, J., Comblen, R., Legat, V., Remacle, J.-F., 2013. Multirate time stepping for accelerating explicit discontinuous Galerkin computations with application to geophysical flows. Internat. J. Numer. Methods Fluids 71, 41–64.
Sharp, G.D., 1988. Fish populations and fisheries: their perturbations, natural and man induced. In: Postma, H., Zijlstra, J.J. (Eds.), Continental Shelvesand. In: Ecosystems of the World, vol. 27, Elsevier, Amsterdam, pp. 155–202.
Shchepetkin, A.F., McWilliams, J.C., 2003. A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate. J. Geophys. Res. 108 (3090).
Shchepetkin, A., McWilliams, J.C., 2005. The regional oceanic modeling system: A split-explicit, free-surface, topography-following-coordinate ocean model. Ocean Model. 9, 347–404.
Sherwood, C.R., Aretxabaleta, A.L., Harris, C.K., Rinehimer, J.P., Verney, R., Ferré, B., 2018. Cohesive and mixed sediment in the regional ocean modeling system (ROMS v3.6) implemented in the Coupled Ocean–Atmosphere–Wave–Sediment Transport Modeling System (COAWST r1234). Geosci. Model. Dev. 11, 1849–1871.
Shi, F., Chickadel, C.C., Hsu, T.J., Kirby, J.T., Ma, G., 2017. High-resolution non-hydrostatic modeling of frontal features in the mouth of the columbia river. Estuar. Coast. 40 (1), 296–309.
Shi, J., Shi, S., Kirby, J.T., Ma, G., Wu, G., Tong, C., Zheng, J., 2015. Pressure decimation and interpolation (PDI) method for a baroclinic non-hydrostatic model. Ocean Model. 96 (2), 265–279.
Silva-Araya, W.F., Santiago-Collazo, F.L., Gonzalez-Lopez, J., Maldonado-Maldonado, J., 2018. Dynamic modeling of surface runoff and storm surge during hurricane and tropical storm events. Hydrology 5 (1), 13.
Skyllingstad, E.D., Denbo, D.W., 1995. An ocean large-eddy simulation of Langmuir circulations and convection in the surface mixed layer. J. Geophys. Res. Ocean. 100 (C5), 8501–8522.
Smyth, W.D., Moum, J.N., 2000. Length scales of turbulence in stably stratified mixing layers. Phys. Fluids 12 (1327).
Soulsby, R.L., Damgaard, J.S., 2005. Bedload sediment transport in coastal waters. Coastal Eng. 52 (8), 673–689.
Soulsby, R.L., Manning, A.J., Spearman, J., Whitehouse, R.J.S., 2013. Settling velocity and mass settling flux of flocculated estuarine sediments. Mar. Geol. 339, 1–12.
Spalart, P.R., 2000. Trends in Turbulence Treatments, AIAA Paper 2000–2306.
Stelling, G.S., 2012. Quadtree flood simulations with sub-grid dems. Water Management 165 (10), 567–580.
Sterling, M.C., Bornner, J.S., Ernest, A.N.S., Page, C.A., Autenrieth, R.L., 2005. Application of fractal flocculation and vertical transport model to aquatic sol–sediment systems. Water Res. 39 (9), 1818–1830.
Styles, R., Glenn, S.M., 2000. Modeling stratified wave and current bottom boundary layers on the continental shelf. J. Geophys. Res. Ocean. 105 (C10), 24, 119–24, 139.
Sullivan, P.P., Patton, E.G., 2011. The effect of mesh resolution on convective boundary layer statistics and structures generated by large-eddy simulation. J. Atmos. Sci. 68, 2395–2415.
Thomas, L.N., Tandon, A., Mahadevan, A., 2013. Submesoscale processes and dynamics. In: Hecht, M.W., Hasumi, H. (Eds.), Ocean Modeling in an Eddying Regime.
Tolman, H.L., 2009. User Manual and System Documentation of WAVEWATCH III Version 3.14. NOAA / NWS / NCEP / MMAB Technical Note 276. 194 pp.
Uchiyama, Y., McWilliams, J.C., Shchepetkin, A.F., 2010. Wavecurrent interaction in an oceanic circulation model with a vortex force formalism: application to the surf zone. Ocean Modell. 34 (1–2), 16–35.
Uittenbogaard, R., 2003. Modelling turbulence in vegetated aquatic flows. In: International Workshop on Riparian Forest Vegetated Channels: Hydraulic, Morphological and Ecological Aspects, Trento, Italy, 20–22 February 2003.
Umlauf, L., Burchard, H., 2003. A generic length-scale equation for geophysical turbulence models. J. Marine Res. 61, 235–265.
Umlauf, L., Burchard, H., 2005. Second-order turbulence closure models for geophysical boundary layers, A review of recent work. Cont. Shelf Res. 25, 795–827.
Umlauf, L., Burchard, H., Hutter, K., 2003. Extending the k–ω turbulence model towards oceanic applications. Ocean Model. 5, 195–218.
Vallaeys, V., Kärnä, T., Delandmeter, P., Lambrechts, J., Baptista, A.M., Deleersnijder, E., Hanert, E., 2018. Discontinuous Galerkin modeling of the Columbia River's coupled estuary-plume dynamics. Ocean Model. 124, 111–124.
Verney, R., Lafite, R., Brun-Cotton, J.C., Le Hir, P., 2011. Behaviour of a floc population during a tidal cycle: Laboratory experiments and numerical modelling. Cont. Shelf Res. 31 (10), S64–S83.
Vitousek, S., Fringer, O.B., 2011. Physical vs. numerical dispersion in nonhydrostatic ocean modeling. Ocean Model. 40 (1), 72–86.
Wang, B., Cao, L., Micheli, F., Naylor, R.L., Fringer, O.B., 2018. The effects of intensive aquaculture on nutrient residence time and transport in a coastal embayment. Environ. Fluid Mech. 18 (6), 1321–1349.
Warner, J.C., Armstrong, B., He, R., J. B. Zambon, J.B., 2010. Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system. Ocean Model. 35 (3), 230–244.
Warner, J.C., Sherwood, C.R., Arango, H.G., Signell, R.P., 2005. Performance of four turbulence closure models implemented using a generic length scale method. Ocean Model. 8, 81–113.
Warner, J.C., Sherwood, C.R., Signell, R.P., Harris, C., Arango, H.G., 2008. Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model. Comput. Geosci. 34, 1284–1306.
Warrick, J.A., Farnsworth, K.L., 2017. Coastal river plumes: Collisions and coalescence. Prog. Oceanogr. 151, 245–260.
van der Wegen, M., Roelvink, J.A., 2008. Long-term morphodynamic evolution of a tidal embayment using a two-dimensional, process-based model. J. Geophys. Res. 113, C03016.
Wengrove, M.E., Foster, D.L., 2014. Field evidence of the viscous sublayer in a tidally forced developing boundary layer. Geophys. Res. Lett. 41, 5084–5090.
Westerink, J.J., Luettich, R.A., Blain, C.A., Scheffner, N.W., 1994. ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts and Estuaries. Report 2: Users' Manual for ADCIRC-2DDI, Department of the Army US Army Corps of Engineers, Washington, D.C.
Whitehouse, R.J.S., Hardisty, J., 1988. Experimental assessment of two theories for the effect of bedslope on the threshold of bed load transport. Mar. Geol. 79, 135–139.
Whittle, K.J., 1997. Marine organisms and their contribution to organic matter in the oceans. Mar. Chem. 5, 318–411.
Wiberg, P.L., Harris, C.K., 1994. Ripple geometry in wave- dominated environments. J. Geophys. Res. 99 (C1), 775–789.
Wilkin, J., Rosenfeld, L., Allen, A., Baltes, R., Baptista, A., He, R., Hogan, P., Kurapov, A., Mehra, A., Quintrell, J., Schwab, D., Signell, R., Smith, J., 2017. Advancing coastal ocean modelling, analysis, and prediction for the US integrated ocean observing system. J. Oper. Oceanogr. 10, 115–126.
Wilmott, C., 1981. On the validation of models. Phys. Geogr. 2, 184–194.
Winterwerp, J.C., van Kesteren, W.G.M., 2004. Introduction to the Physics of Cohesive Sediment in the Marine Environment. Elsevier, The Netherlands.
Winterwerp, J.C., Manning, A.J., Martens, C., de Mulder, T., Vanlede, J., 2006. A heuristic formula for turbulence-induced flocculation of cohesive sediment. Estuar. Coast Shelf. S. 68, 195–207.
Wolfram, P.J., Fringer, O.B., 2013. Mitigating horizontal divergence 'checker-board' oscillations on unstructured triangular C-grids for nonlinear hydrostatic and nonhydrostatic flows. Ocean Model. 69, 64–78.
Xue, Z., He, R., Liu, J.P., Warner, J., 2012. Modeling transport and deposition of the Mekong River sediment. Cont. Shelf. Res. 37, 66–78.
Ye, F., Zhang, Y., Wang, H., Friedrichs, M.A.M., Irby, I.D., Alteljevich, E., Valle-Levinson, A., Wang, Z., Huang, H., Shen, J., Du, J., 2018. A 3D unstructured-grid model for Chesapeake Bay: importance of bathymetry. Ocean Model. 127, 16–39.
Yool, A., Fasham, M.J., 2001. An examination of the "continental shelf pump" in an open ocean general circulation model. Global Biogeochem. Cy. 15 (4), 831–844.
Yoon, H.-D., Cox, D.T., Kim, M., 2013. Prediction of time-dependent sediment suspension in the surf zone using artificial neural network. Coastal Eng. 71, 78–86.
Yu, X., Ozdemir, C., Hsu, T.-J., Balachandar, S., 2013. Numerical investigation of turbulence modulation by sediment-induced stratification and enhanced viscosity in oscillatory flows. J. Waterw. Port Coast. 140 (2), 160–172.
Zambon, J.B., He, R., Warner, J.C., 2014a. Investigation of Hurricane Ivan using the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) model. Ocean Dynam. 64 (11), 1535–1554.
Zambon, J.B., He, R., Warner, J.C., 2014b. Tropical to extratropical: Marine environmental changes associated with Superstorm Sandy prior to its landfall. Geophys. Res. Lett. 41, 8935–8943.
Zeller, R., B, Weitzman, J.S., Abbet, M.E., Zarama, F.J., Fringer, O.B., Koseff, J.R., 2014. Improved parameterization of seagrass blade dynamics and wave attenuation based on numerical and laboratory experiments. Limnol. Oceanogr. 59.
Zhang, Y., 2017. Numerical Modeling for Hydrodynamics and Suspended Sediment Transport in Estuarine Marshes (Ph.D. thesis). Stanford University.
Zhang, Y., Ateljevich, E., Yu, H-C., Wu, C-H., Yu, J.C.S., 2015. A new vertical coordinate system for a 3D unstructured-grid model. Ocean Model. 85, 16–31.
Zhang, Y., Baptista, A.M., 2008. SELFE: A semi-implicit Eulerian–Lagrangian finite-element model for cross-scale ocean circulation. Ocean Model. 21, 71–96.
Zhang, J., Chu, D., Wang, D., Cao, A., Lv, X., Fan, D., 2018. Estimation of spatially varying parameters in three-dimensional cohesive sediment transport models by assimilating remote sensing data. J. Mar. Sci. Technol. 23 (2), 319–332.
Zhang, J., Lu, X., Wang, P., Wang, Y.P., 2011. Study on linear and nonlinear bottom friction parameterizations for regional tidal models using data assimilation. Cont. Shelf Res. 31 (6), 555–573.
Zhang, Y., Ye, F., Stanev, E.V., Grashorn, S., 2016. Seamless cross-scale modeling with SCHISM. Ocean Model. 102, 64–81.
Zijlema, M., Stelling, G., Smit, P., 2011. SWASH: An operational public domain code for simulating wave fields and rapidly varied flows in coastal waters. Coastal Eng. 58 (10), 992–1012.