Preparing a Workforce for the New Blue Economy

People, Products and Policies

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CHAPTER 4

Ocean modeling

Eric P. Chassignet
Center for Ocean-Atmospheric Prediction Studies (COAPS), Florida State University, Tallahassee, FL, United States

Introduction

Ocean modeling is a relatively new course of study within the field of oceanography that emerged in the 1960s and has experienced rapid growth due to the exponential increase in computer processing capabilities (Chassignet et al., 2019). Over the past decade, improved understanding, numerics, grid configurations, spatial discretization, parameterizations, data assimilation, environmental monitoring, and process-level observations/modeling have led to significant advances in ocean circulation modeling (see Fox-Kemper et al. (2019) for a review). Enhanced computational capabilities and greater physical consistency in numerical formulations (Griffies et al., 2000) have made routine resolution of oceanic flows possible at the mesoscale on global scales, at the submesoscale on regional scales, and to detailed harbor structures in the coastal ocean (e.g., Álvarez-Fanjul et al., 2018; De Mey-Frémaux et al., 2019). Ocean circulation models have expanded our ability to identify and characterize complex and diverse physical mechanisms in the ocean. They can also be incorporated into data assimilative frameworks to produce forecasts on a variety of timescales. They can be used to produce seasonal to decadal forecasts when coupled to atmospheric circulation models, and when fully integrated into earth system models (ESMs), ocean circulation models are an essential component of climate modeling. ESMs seek to simulate all relevant aspects of the Earth system, and by integrating the interactions of atmosphere, ocean, land, ice, and biosphere, they can be used to estimate the state of the ocean under a wide variety of conditions. In practice, ocean numerical models consist of a discretized solution to a set of partial differential equations describing the ocean dynamics that are based on an approximated version of Navier–Stokes equations (Griffies, 2004; Griffies and Treguier, 2013). Ocean numerical models are typically written in FORTRAN, consisting of 20,000–200,000 lines of code, and they can take up to a decade in community development before they are fully functional (Fox-Kemper et al., 2019).

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Ocean models can be used to generate idealized or realistic configurations that allow us to explore fundamental ocean mechanisms. However, in order to build a physically consistent estimate of the ocean state, its evolution, and ultimately reanalysis products that can describe past evolution, ocean models are combined with data assimilation techniques to extrapolate in space and time the sparse oceanic observations (Ferry et al., 2012; Carton et al., 2018; Wunsch, 2018). The same data assimilation techniques are used to generate the initial state that is used to perform short-term forecasts (Chassignet and Verron, 2006; Dombrowsky et al., 2009; Schiller and Brassington, 2011; Bell et al., 2015; Chassignet et al., 2018). Observational data via data assimilation pave the way for model state estimates and forecasts (Chassignet et al., 2009), the quality of which is strongly dependent upon an ocean numerical model's ability to accurately represent not only the ocean dynamics that is resolved by the model grid, but also the unresolved physics via subgrid-scale parameterizations.

Operational oceanography

Operational oceanography is defined as the systematic and long-term routine measurement of the oceans and their rapid interpretation and dissemination. Ocean forecasting, as a component of operational oceanography, is based on the near-real-time collection of ocean observations that are assimilated into ocean numerical models to provide forecasts (5—10 days) (Schiller et al., 2018; Davidson et al., 2019). Ocean numerical models are a key component of global, regional, and coastal operational oceanography systems. A comprehensive operational system contains models that solve governing equations for ocean currents (u, v), sea levels, temperature (T), salinity (S), sea ice, surface waves, and concentrations of tracers relevant to environmental or biogeochemical processes. Biogeochemical forecasting systems are a combination of existing physical forecasting systems and biogeochemical models developed either for climate research or for ecological modeling (Ford et al., 2018).

In order for operational oceanography to be of maximum use, an accurate representation of large-scale upper ocean structure and mesoscale features, such as eddies and meandering fronts, is required (Fig. 4.1) (Hecht and Hasumi, 2008). Most of the improvements in the representation of these features during the past 10 years is the direct result of more powerful computing platforms that allow for increased horizontal resolution. We can now perform basin-scale simulations with grid spacing on the order of 1 km

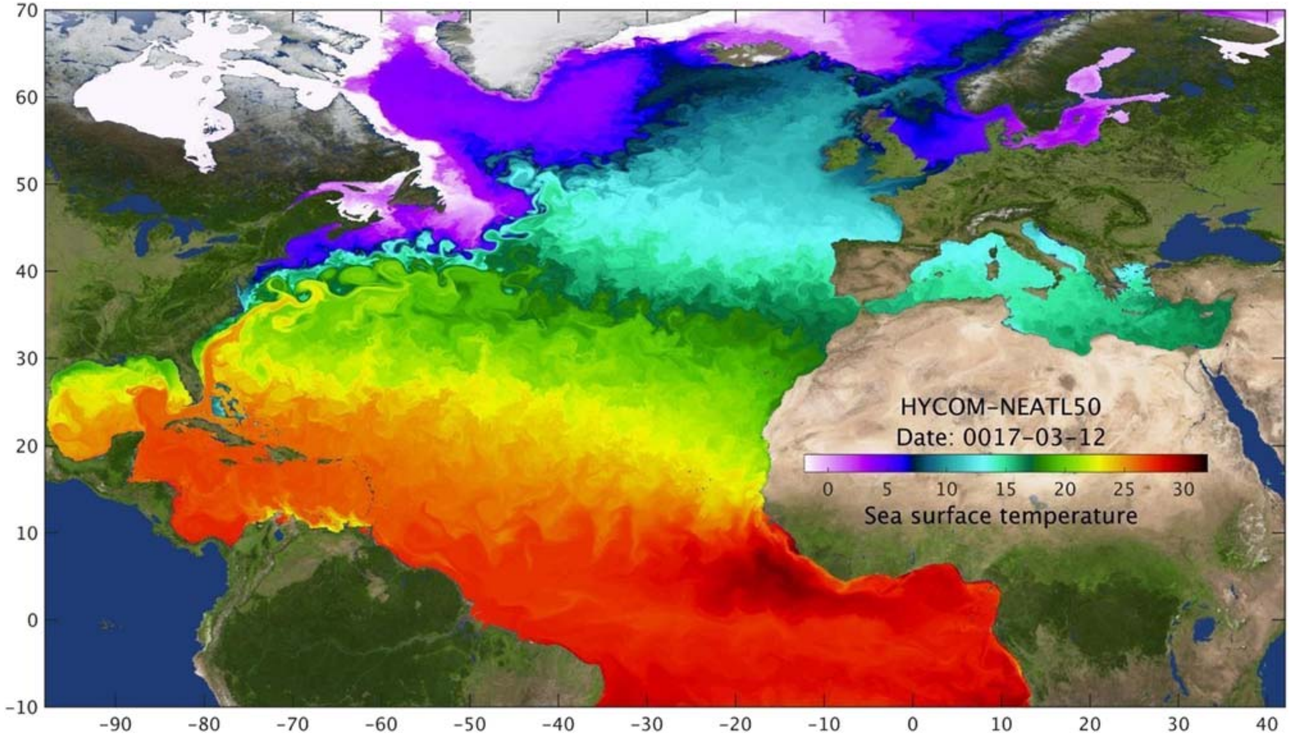

Figure 4.1 Sea surface temperature snapshot for the North Atlantic and Equatorial Ocean from a 1/50° (~1.5 km at mid-latitudes) HYCOM numerical simulation (Chassignet and Xu, 2017). Noteworthy are the Loop Current in the Gulf of Mexico, the Gulf Stream separating at Cape Hatteras, the Gulf Stream penetrating, meandering, and shedding eddies into the ocean interior, and tropical instability waves in the equatorial region.

(submesoscale resolving) (Chassignet and Xu, 2017; Ajayi et al., 2020, 2021) and regional simulations with grid spacing on the order of 100 m (Capet et al., 2008). However, these models are not able to account explicitly for the full range of scale interactions that regulate ocean circulation. Because oceanic flows are turbulent in nature, ocean circulation at a given scale is fundamentally dependent on oceanic motions at scales ranging from global (of order 10,000 km) to dissipative (of order 1 cm). Further, the scales of motions explicitly represented in a particular model's solution will be constrained by the predetermined grid resolution of the model configuration. Subgrid-scale parameterizations are needed to account for the important physical processes that are not resolved. Parameterization choices have a profound impact on the physical representation of boundary currents (Chassignet and Xu, 2017) and on biogeochemical processes since they are quite sensitive to small-scale processes (Ford et al., 2018).

In addition to capturing and predicting large-scale ocean features, operational systems are needed to help predict the array of spatial and temporal scales that are found near coastlines (De Mey-Frémaux et al., 2019). Coastal oceans are geometrically constrained by jagged coastlines and irregular bathymetry; they are driven (internally, laterally, and at the surface) on a large range of space/timescales by buoyancy, wind, and tidal forces (Haidvogel et al., 2000). The subsequent coastal circulation patterns include both persistent and time-variable fronts, intense currents with strong spatial (offshore and/or vertical) dependence, coastal trapped waves, internally generated mesoscale variability, large horizontal water mass contrasts, strong vertical stratification, and regions of intense turbulent mixing in both surface and bottom boundary layers. This results in an observational as well as a modeling challenge and requires the development of coastal ocean forecasting systems capable of supporting societal and management decisions and policy (Kourafalou et al., 2015a,b). Coastal models, therefore, need to be able to resolve interactions between nearshore, estuarine, and shelf processes (required resolution of 10—100 m), as well as open ocean processes (required resolution of 1—10 km). Consequently, coastal numerical models are typically nested within a regional or global model configuration (Katavouta and Thomson, 2016; Holt et al., 2017; De Mey-Frémaux et al., 2019). Coastal regions present an advantage in that permanent, multivariate instrumented sites are easier to set up than global ocean observing systems and coastal observatories can employ many data sources that are not available for the open ocean. For example, technologies such as telemetering moorings and fixed platforms, profiling floats, autonomous underwater vehicles (AUVs), Lagrangian drifters, and surface current measuring radar can be deployed regionally. These observational technologies are complemented by global satellite observing networks and direct in situ observations of the subsurface ocean. By combining coastal modeling systems and comprehensive observational networks, coastal ocean forecasting systems facilitate the constant monitoring of variations in the coastal ocean and support forecasting activities. This, in turn, allows for the delivery of useful and reliable ocean services, such as forecasting, sustainable management of ecosystems, shipping efficiency, mitigation of storm damage, etc.

As stated by Schiller et al. (2018), further advances in operational oceanography will require increasingly multidisciplinary efforts in physics, chemistry, biology, geomorphology (especially in the littoral zone), and information technology/visualization, as well as the exploitation of "big data" expertise given the petabytes of model outputs generated. Apart from the scientific challenges, continued expansion of operational oceanography will require the recognition of the collective benefit of all its constituents (observations, data management, prediction system, production/service delivery, and clients). In particular, the satellite and in situ elements of physical observing systems, as well as the sustainability and expansion of biological and biogeochemical observing systems, are vital components of ocean forecasting systems. The introduction of "intelligent" in situ sensors, sensor networks/webs, and new and/or improved remote sensing technologies will also create new opportunities. Finally, the development of open-access web data services aligned with community conventions for metadata descriptions has been shown to foster systems' data exchange and model usage, accelerate testing, validate the acceptance cycle for modeling system enhancements, simplify the addition of new data streams, enable operational monitoring, and allow novice users to view and download model outputs to become the basis for higher-level ocean information products (Wilkin et al., 2018).

Earth system modeling (ESM)

Variations of ocean circulation are dynamically coupled with that of sea ice, waves, and atmospheric physics. Ocean circulation models are only one component of an ESM. The coupled systems that form an ESM allow for improved representation of physical processes across oceanic boundaries, which is necessary for short-range forecasts as well as for seasonal to climate timescales (Brassington et al., 2015). As stated by Harris et al. (2018), the value of genuinely coupled models is that adjustments in one model can immediately and proximately influence the other model. For example, the lack of any feedback in ocean-only models on atmospheric forcing variables, such as temperature, winds, or humidity, can result in erroneousness (see e.g., Griffies et al., 2009). This is especially true if the atmospheric forcing used is obtained from an atmosphere model integrated with a significantly different ocean surface boundary condition. Differences in areas of ice cover are especially problematic in this regard because heat and moisture fluxes over the open ocean are very different from those over sea ice. Also, a high-resolution coupled system of the coastal ocean that takes into account the nonlinear feedback between the atmosphere and the upper ocean via a wave interface will reduce ocean prediction errors, particularly under extreme conditions (Staneva et al., 2017; De Mey-Frémaux et al., 2019). Deterministic modeling systems are fairly accurate when applied to short-term weather time scales. However, longer subseasonal-to-seasonal scales require ensemble-based modeling systems that can represent the inherent uncertainty and predictability. Several competing priorities exist as such modeling systems continue to evolve. First, is the need for refined resolution to improve the fidelity of resolved flow features. Second, the representation of otherwise missing processes and feedbacks will require increased component complexity/capability. And third, extraction of a signal from the noise will require more ensemble members (Hewitt et al., 2017). Further, in order to fully incorporate biogeochemical models in the forecasting systems, additional work will be needed (see next section for an example).

Initially, the scales at which ocean circulation models were able to represent oceanic properties and physical processes were significantly larger than the mesoscale (horizontal scales in the neighborhood of 100 km and approximately 3-month timescales). However, in order to be of maximum use, the ocean circulation model component of an ESM must be able to represent the wide range of oceanic physical processes that today's ocean models are capable of as a result of increases in computing power and of the improved physical consistency of their formulations. For example, today's global ocean circulation models are able to resolve oceanic flows down to the submesoscale (horizontal scales on the order of 10 km or less; Chassignet and Xu, 2017) and to account for internal wave and internal tides (Shriver et al., 2012). Fig. 4.2 shows the impact of increasing horizontal grid spacing on the representation of small-scale features in the Gulf of Mexico.

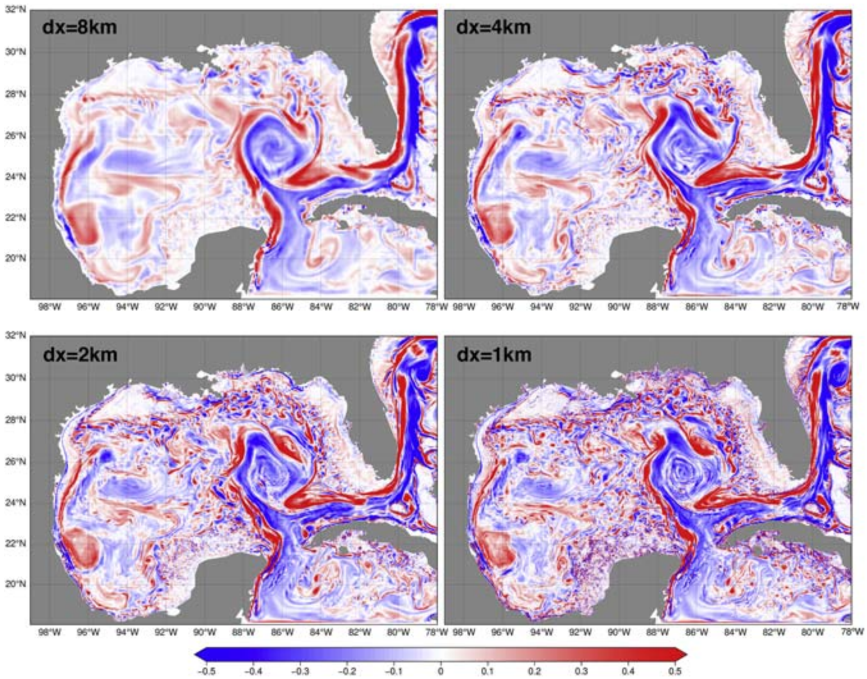

Figure 4.2 Modeled Gulf of Mexico surface relative vorticity (ζ/f with $f = 10^{-4}\ s^{-1}$) depicting the flow rotation and shear as a function of horizontal grid spacing (8, 4, 2, and 1 km, respectively). In addition to the loop current penetrating in the Gulf interior and large separated loop current eddies, one can observe an increased number of small-scale features that arise when the model horizontal resolution is increased.

Example: Gulf of Mexico oil spill modeling

The 2010 Deepwater Horizon (DwH) oil spill occurred in an area that encompasses a broad variety of oceanographic environments and ecosystems. The DwH spill originated over the deep outer shelf, where it could potentially have been transported seaward over the abyssal region of the Gulf of Mexico or onto shelves of varying width and toward coasts with sandy shores or wetlands. One of the most important components of this area's circulation, hydrography, and biogeochemistry is the Mississippi River. Among other things, the river supplies nutrients fueling productivity, freshwater that contributes to upper ocean stratification, and sediments that can interact with oil in the water column. Over the Texas–Louisiana shelf to the west, seawater properties (temperature, salinity, turbidity, and currents) are very different than what is found in the deeper location of DwH, and low oxygen (hypoxic) conditions occur each summer. While analysis of the DwH surface oil transport shows that a relatively small fraction of oil from the spill drifted over the Texas–Louisiana shelf, under different forcing regimes, a substantial quantity of the oil could have advected over this shelf and been deposited on the seafloor through sedimentation/flocculation. Further, it is presumed that microbial activities, which are quite significant and diverse in these areas, have a substantial impact on biodegradation and the accumulation of petroleum in the water column and marine sediments of the deep ocean. Given that toxic oil constitutes unknown threats to benthic organisms, many of which are harvested for human consumption, the ability to predict the eventual fate of oil and its impact on ecosystems is critical. Additionally, ongoing oil and gas extraction activities taking place in the Gulf of Mexico increase the likelihood of large spills in the future.

Ocean circulation models increase our ability to understand this complex system and associated diverse physical mechanisms. And now that critical novel interactions, such as hydrocarbon biodegradation and flocculation, can be represented in the coupled system (Morey et al., 2020), a modeling framework can be used to simulate oil in the marine environment, including its interaction with ecosystems and sediments and predict where ecosystems may be affected. So, whereas biodegradation might have been included in oil models for removal of oil from the system as a simple decay parameterization, in reality it is a complex process mediated by diverse microbial taxa that convert hydrocarbons into biomass, carbon dioxide, and more refractory forms of organic carbon. Similarly, flocculation is commonly included via parameterizations in sediment transport models, but the formulations used have rarely accounted explicitly for either the biological constituents of the water column or the presence of oil. Yet, flocculation is likely to be an important link facilitating transport between oil in the water column and the sediments at the seafloor, both in deep water and over the shelf. The role of flocculation is especially important within turbid river plumes and during storms when significant resuspension occurs. Fig. 4.3 shows a snapshot from the DwH oil model developed by the Consortium for Simulation of Oil-Microbial Interactions in the Ocean (CSOMIO, http://CSOMIO.org). CSOMIO has developed a modeling system that dynamically couples components for simulating ocean hydrodynamics, oil transport, dispersion and weathering, oil-mineral aggregate (OMA) formation, flocculation and settling, and the lower trophic-level marine ecosystem (Dukhovskoy et al., 2021). It is an adaptation and extension of the Coupled Ocean-Atmosphere-Wave-Sediment

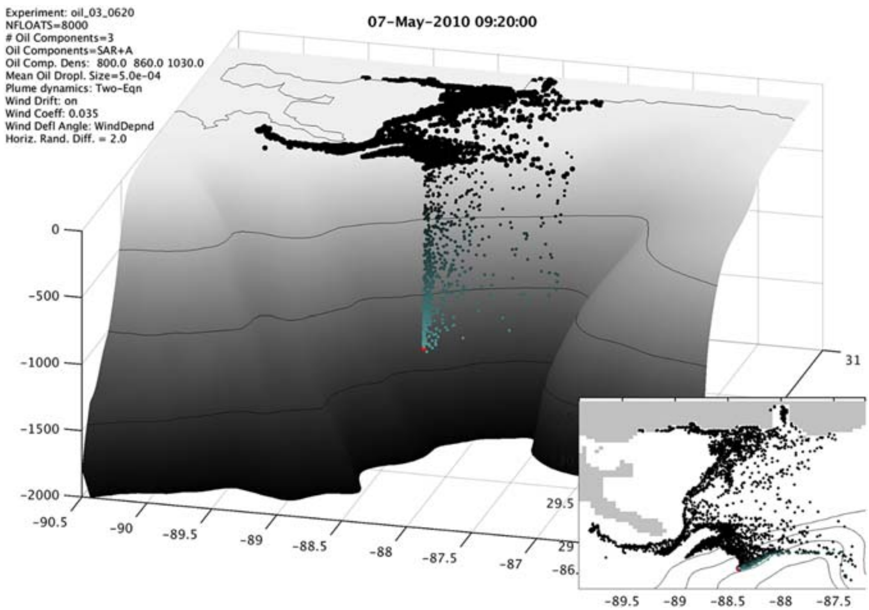

Figure 4.3 Modeled vertical and horizontal distribution of oil on May 7, 2010. The CSOMIO oil plume model is based on a Lagrangian approach that describes the oil plume dynamics by advecting and diffusing individual "floats" representing a cluster of oil droplets. The chemical composition of oil is described in terms of three components (saturates, aromatics, and heavy oil including resins and asphaltenes). Oil droplets are characterized by size and chemical structure (mass fraction of compounds). The oil plume model simulates rise velocity of oil droplets based on ambient ocean flow and density fields and density and size of the oil droplets. The oil model also includes weathering processes and surface wind drift. A key component of the CSOMIO model is Lagrangian–Eulerian and Eulerian–Lagrangian mapping of the oil characteristics. This mapping is necessary for the interaction between the ocean-oil module with the sediment and biology models.

Transport (COAWST) modeling system (Warner et al., 2010). A biogeochemical modeling component incorporating a microbial model (Genome-based EmergeNt Ocean Microbial Ecosystem (GENOME); Coles et al., 2017) is implemented in the system and adapted for the presence of hydrocarbons. The sediment transport component of COAWST (the Community Sediment Transport Modeling System, CSTMS) is modified to include computationally efficient flocculation parameterizations for OMAs developed from laboratory experiments. The ocean modeling component of COAWST (the Regional Ocean Modeling System, ROMS) is modified to simulate three-dimensional oil transport and compositional changes (weathering). These modeling components are linked together using a two-way Lagrangian–Eulerian mapping technique enabling interaction between all of the modeling components for tracking of hydrocarbons from a source blowout to deposition in sediment, microbial degradation, and evaporation while being transported through the ocean. This component can be run offline to increase computational speed.

Perspective

Ocean circulation model design is an active field of study that has matured, in large part, because of strong cross-disciplinary collaborations and the consolidation of efforts among different groups involved in the various applications and dimensions of ocean circulation and ESMs. Ocean circulation model design often calls for entire scientific teams focused on the development or improvement of models. Continued improvement to ocean circulation models depends heavily upon ocean observing networks and the critical role that sustained satellite observations and in situ observations play in the routine assessment of model skills and limitations over different timescales ranging from days to decades. A great deal can be learned from targeted field observations geared toward documenting specific oceanic processes so that they can be better represented in ocean models.

In order to meet the evolving needs of operational oceanography and ESM end users, ocean circulation models will need to be able to account explicitly for a comprehensive range of physical scales due to the multiscale nature of oceanic flows. Improving the performance of ocean circulation models on modern high-performance computing platforms will allow for broadening the spectrum of resolved scales in the models by increasing the horizontal and vertical resolution. The current trend is toward massively parallel machines with heterogeneous multicore architectures (Giles and Reguly, 2014). But while modern platforms can deliver a peak performance in the Petaflops range, existing ocean circulation models are unable to fully exploit this potential. The computational intensity (i.e., floating point operations per memory access) of ocean models is very low because they are dominated by stencil operations (typical of discretized partial differential equations) and typically run at ~5% of the peak speed of the system. Also, ocean models have a very small vertical dimension, typically O(10), so they scale more like 2-D domains than 3-D domains. The ability of an ocean model to take advantage of massively parallel computers is limited by the communication overhead, load imbalance, latency, and inputs/outputs overhead inherent to the spatial 2-D domain decomposition cores one has to make to distribute the tasks evenly to all the processors. Sustained collaborations between ocean modelers and computer scientists will be needed to overcome single processor and scalability issues (Chassignet et al., 2019). Practical approaches will likely involve more hybrid parallel programming in order to more efficiently exploit memory hierarchy and innovative algorithms for solving the set of partial differential equations that govern ocean dynamics, for instance, parallelization in time in addition to spatial domain decomposition (Schreiber et al., 2017).

A quick Internet search for "ocean modeling jobs" shows that there is great demand for ocean modeling computing skills. This is driven by several factors. In academia, the emphasis on climate research not only implies strong cross-disciplinary collaborations, but a need for students and postdocs with good programming skills to further develop and refine ESMs. The main challenge facing academia in attracting young and talented programmers is an incompatibility between model developments that may require many years to reach fruition and high rates of publication now becoming the norm for advancement of early career scientists.

There is also a strong need for qualified applicants in government laboratories because there is a push to develop the next generation of ESMs to address national needs. For example, in a bid to regain global leadership in weather forecasting, the National Oceanic and Atmospheric Administration (NOAA) is establishing an Earth Prediction Innovation Center (EPIC) to address longstanding challenges in translating research advances into operational forecasts (https://owaq.noaa.gov/Programs/EPIC). This center will accelerate community-developed scientific and technological advancements into the operational applications for numerical weather prediction by supporting a Unified Forecast System (UFS) community model. NOAA is working closely with entities in the weather enterprise (public, private, and academic) to accelerate the transition of research to operations, share the current status and future of community-based ESM, and identify emerging technologies. The Energy Exascale Earth System Model (E3SM) project at the US Department of Energy (DOE) is another example of an ongoing, state-of-the-science earth system modeling, simulation, and prediction project that optimizes the use of DOE laboratory resources to meet the science needs of the nation and the mission needs of DOE. It focuses on (1) the hydrological cycle and how more realistic portrayals of features important to the water cycle (clouds, aerosols, snowpack, river routing, land use) will affect simulations of river flow and associated freshwater supplies at the watershed scale; (2) uptake of CO_2 by land and ocean ecosystems; and (3) cryosphere—ocean interactions and the impacts of ocean—ice shelf interactions on the melting of the Antarctic ice sheet, the global climate, and sea level rise (https://climatemodeling.science.energy.gov/program/earth-system-model-development).

Ocean modeling employment opportunities in the private sector fall into two categories, one that works closely with government agencies as contractors in order to supplement the federal workforce to address national needs as described earlier and one that provides operational oceanographic products and ocean services to the public at large. Many of these products and services cover a wide range of applications; address real-world issues related to public safety, the maritime industry, and environmental conservation efforts; and are provided and/or disseminated in a systematic and routine manner to end users. Examples include warnings (coastal floods, ice and storm damage, harmful algal blooms and contaminants, oil spill, etc.), optimum routes for ships, and prediction of seasonal or annual primary productivity, ocean currents, ocean climate variability, etc. The field's evolution and fast-paced advances mean that the growth potential for this sector is high, with many future training and job opportunities (see Op-Ed in this volume on the Rutgers Operational Oceanography program). It is fair to say that the multidisciplinary nature of operational oceanography makes it an exciting scientific career path, particularly for those interested in research or the assimilation of new technological advances and methods.

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Preparing a Workforce for the New Blue Economy

People, Products and Policies

Edited by Liesl Hotaling and Richard W. Spinrad

An edited work bringing together multiple sectors to help develop the partnerships and coordination needed to cultivate a workforce to support the New Blue Economy.

The traditional Blue Economy, encompassing ocean energy, seabed mining, transportation, fishing, tourism, aquaculture and marine biotechnology is evolving. This New Blue Economy – a knowledge based, information services economy, based on foundational publicly available data supporting the traditional Blue Economy – is expected to be a multi-billion-dollar enterprise, with a diversity of public and private users.

Preparing a Workforce for the New Blue Economy discusses the emerging opportunity in the New Blue Economy, how the industry will develop, and how to prepare the next generation of developers of ocean data, information, and knowledge. The book considers how to prepare a diverse and inclusive future workforce equitably, including the use of ocean observations, next generation predictive models, big data, key skill sets, changes to undergraduate and graduate programs, and engaging industry, academia, governmental agencies, non-profits, and NGOs. Furthermore, guidance is offered on how to assess the health of the developing New Blue Economy. Finally, a broad range of case studies, op-eds, and interviews are provided, covering oil and gas, commercial fishing, sustainability, and ocean forecasting, to highlight the educational requirements of the future workforce and the potential economic opportunities.

The holistic approach and workforce focus of this authoritative book makes it an ideal reference for those working in the marine industry, academia, and governmental and non-profit ocean communities.

Key features:

- Coordinates efforts from different disciplines and sectors, and shares effective teaching practices and approaches.
- Includes comprehensive case studies highlighting the educational requirements of the workforce and the potential economic opportunities.
- Presents a framework for unifying several workforce sectors dependent upon the ocean and inspiring solutions for sustainability.

Edited by:
Liesl Hotaling, Eidos Education; University of South Florida, St. Petersburg, Florida, USA
Richard W. Spinrad, Oregon State University, Corvallis, Oregon, USA

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