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The Sea: The Science of Ocean Prediction

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At the beginning of the 20th century Vilhelm Bjerknes defined the "ultimate problem of meteorology and hydrography" as the discovery of "the laws according to which an atmospheric or hydrospheric state develops out of the preceding one" and the "precalculation of future states" from gridded analyzed observations—that is, forecasting. The development of the electronic computer and the vision of several meteorologists allowed the transformation of meteorology into a sophisticated scientific discipline based on physics and mathematics. The first successful meteorological forecast was carried out in the 1950s. Meteorological forecasting became an operational activity at the end of the 1960s. The contributions to society of such operations have been tremendous.

Ocean forecasting began in the 1980s with a joint venture between Harvard University and the Naval Postgraduate School in Monterey, California, that completed the first successful forecast of ocean mesoscales in a limited area of the ocean. Since then, computational ocean modeling and prediction have led to major discoveries across multiple time and space scales, from ocean turbulence to climate. In the first decades of the 21st century, ocean forecasting has become an operational activity. The rapidly increasing interconnectivity between humans and the Earth system suggests that ocean prediction will become ever more vital to society in the years to come.

Ocean prediction is now part of the wider human endeavor to understand, monitor, and forecast whole-earth physical and biogeochemical dynamics and cycles. The science of ocean prediction is *the systematic development of fundamental knowledge about ocean dynamics in the form of testable ocean models and estimation systems that relate to forecasting the ocean's evolution*. It includes governing laws, model equations, parameterizations, numerical implementation, data-driven computational integration, and evaluation of models and systems outputs against ocean observations. Central to the science is the acquisition of relevant observational data sets and the development of models and numerical techniques, together with data assimilation schemes that quantitatively meld all information sources in accord with the uncertainties of the observations and models. It is the sustained combination of observations with models that can control nonlinear error growth and address the "limit of predictability" of ocean and atmospheric dynamics.

In addition, the systematic testing of models with observations motivates two activities that are fundamental to all sciences: the collection of new and more representative data and the development of more accurate models. With the advent of machine learning, these fundamental activities can be formalized through adaptive sampling and adaptive model learning. In modern ocean prediction, stochastic approaches and (super)-ensemble estimates complement deterministic solutions, accounting for the multiple ocean scales and the need to predict the variability and the statistics of ocean dynamics.

Much research is needed to advance ocean prediction, including: (1) innovative autonomous multi-scale observing technologies, both remote and in situ; (2) multi-dynamic, multi-scale, multi-fidelity ocean modeling; (3) next-generation multi-resolution computational methods and data assimilation schemes; (4) integration and coupling with models and systems for Earth system dynamics; and (5) methodologies to evaluate the quality of estimates and to learn new models or future observation needs.

Ocean prediction will continue to benefit an increasing number of applications. This is because it allows for informed management and emergency decisions to be made based on physical, chemical, and biological knowledge resolved at unprecedented space and time resolution, with known quality and accuracy. The emergence of operational organizations for delivering real time forecasts and analyses will encourage the development of value-added end-user products. These products include forecasts for extreme weather-driven events (such as storm surges), pollution, oil spills, acoustic properties (for example, the speed of sound), sea ice, ecosystem management, safe offshore activities, optimal energy extraction, and maritime transport. Such applications and operational products contribute to advancing ocean science because they spawn new technologies that lead to future discoveries, but also because they can themselves directly lead to new understanding.

The content of *The Sea: The Science of Ocean Prediction* should offer a valuable reference for scientists and engineers interested in any aspect of ocean prediction. The complete volume is dedicated to the late Allan R. Robinson, whose pioneering work in ocean forecasting of mesoscale eddies will continues to inspire future generations of students and scientists.