Oceanographers’ contribution to climate modelling and prediction: progress to date and a future perspective

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The ocean plays an essential role in determining aspects of the climate through its influence on coupled processes involving the atmosphere, cyrosphere and biogeochemistry, including budgets of heat and carbon dioxide and sea-level rise. Here, the key developments in ocean modelling over the past 20 years are reviewed and the prospects for the next 20 years are outlined, considering a hierarchy of idealized, conceptual and realistic modelling frameworks. It is emphasized that any long-term modelling strategy needs to be underpinned and complemented by fundamental theoretical and observational research activities. The need to be aware of the societal and technological drivers that will shape future research directions is also articulated.

Keywords: climate modelling; oceanography; Earth system science

1. Introduction

I was asked by the Challenger Society for Marine Science and the UK Scientific Committee on Oceanic Research to consider the role of oceanography in climate modelling and prediction over the past 20 years and to provide a perspective for the next 20 years. Climate modelling encompasses many things. While sophisticated coupled atmosphere–ocean–ice models, and recently more comprehensive Earth system models, are the central tool for generating projections of future climate, simpler models—for example box models or quasi-geostrophic models—also play a central role in helping us understand the key dynamical processes in the ocean and the sensitivities of the climate system. Numerical techniques have also become very beneficial in maximizing the value of observations, whether through data assimilation, inverse modelling or state estimation.

A century ago, Richardson proposed using numerical techniques to solve a version of the Navier–Stokes thermodynamic and continuity equations on a grid over the Earth’s surface to model atmospheric flow and thus predict the weather [1]. With what turns out to be incredible foresight, long before the development of the electronic computer, Richardson [1] famously imagined a large hall like a theatre, the walls painted to form a map of the world, in which ‘a myriad [human]

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One contribution of 11 to a Theme Issue ‘Prospectus for UK marine science’.
computers are at work upon the weather [numerically solving the equations] of the part of the map where each sits’. Today, the approach of numerical simulation remains at the heart of modelling the evolution of both the atmosphere and oceans, and thus of predicting future climate. Richardson [1] also stressed the importance of basic research on geophysical fluid dynamics: ‘In a neighbouring building, there is a research department, where they invent improvements. In a basement an enthusiast is observing eddies in the liquid lining of a huge spinning bowl, but so far the arithmetic proves the better way’. Importantly, Richardson [1] recognized that numerically it would be unfeasible to resolve all scales of motion, stating ‘many varieties of motion which we cannot or do not wish to record in detail, can be ignored; provided that their general statistical effect is taken into account by adding to the equations, describing the general motion, appropriate additional terms’.

Like the atmosphere, the ocean is a stratified rotating fluid, and thus the numerical modelling of the two are rather analogous. The governing equations are similar and in both cases computational constraints mean it is not feasible to resolve all the relevant space and time scales in numerical simulations. Climate prediction requires coupled models of the atmosphere–ocean system to be run in global configurations over decades to millennia. Yet ocean eddies with a typical size of 10–100 km are ubiquitous and dynamically critical, and many of the important oceanic processes have time scales of minutes to hours. Thus, a century after Richardson’s writings, two of the key challenges in ocean modelling for climate prediction remain: (i) understanding the effects of unresolved processes and (ii) determining how best to represent them numerically. The important complementary role of basic research on geophysical fluid dynamics also remains.

Over the past few decades, two developments have provided platforms that can be used to make progress. The first is the increasing availability of computing power that has brought the ocean mesoscale onto the horizon of climate simulations and the submesoscale onto the horizon of global ocean-only simulations. The second is an increasing sophistication in the ways we are able to probe the ocean surface and sub-surface observationally. Taking advantage of these two developments, in combination with traditional theoretical development and carefully designed idealized modelling, will be key to addressing the climate modelling and prediction challenges over the coming decades.

Although it is very difficult to predict the future evolution of the subject, notwithstanding the insightful comments made in an article by Naveria Garabato [6] pointing out that many of the seeds of future successes will have already been set, there is one aspect on which we are in a sense professional clairvoyants. If we believe our own projections, the world will be a very different place in 20 years time. Figure 1 shows the global average temperature projections for different emissions scenarios produced for the IPCC Fourth Assessment Report
According to these projections, in 2032, humanity will be facing a real possibility that globally averaged temperature change will exceed a threshold value of 2°C within the subsequent 20 years [8]. Whatever the socio-economic-political path we take as a global community in the intervening years, the societal challenges that we will be asked to respond to, and the impact that our research can have, will be different in 20 years time. We must start preparing now to address these challenges. Over recent decades, the big questions we have addressed are: is the climate changing, and is that change largely human-induced? Already, questions such as how might we adapt to climate change, or indeed how might we modify our climate through geoengineering, have started to become more prominent. Although the basic human desire for ‘discovery’ will always remain (and the opportunity to do science for science’s sake should be defended, not least because that curiosity is an integral part of what it means to be human), we must be aware too of the societal and technological drivers that will shape our future research directions. But while responding to these drivers we also need to be very clear in articulating the fact that the tree of evidence upon which policies and decisions can be made has at its roots basic research, possibly conducted many years ago.
years before. Thus, a sophisticated response to societal and technological drivers will encompass applied research that can be directly used to address real-world challenges (the leaves of the tree), fundamental research to lay the foundations for future progress (the roots) and a strong set of links in between (the trunk and branches).

In this article, I will first review some of the advances in ocean modelling over the past 20 years, noting the key steps to progress over this time. I will then comment on the current state and future direction. Finally, I will lay out some of the future opportunities and challenges, their societal and scientific drivers and the critical steps that will need to be taken to enable the challenges to be addressed.

2. A look back 20 years

In whatever sphere one looks back at the last 20 years—political, technological, social or scientific—it is striking both how much and how little has changed. Looking back at the past 20 years of climate modelling and prediction, and in particular at the contribution of oceanography, is no exception. The first report of the Intergovernmental Panel on Climate Change was released in 1990 [9]. At the time, it was recognized that the large-scale transports of heat and freshwater by the ocean circulation are important for determining the overall magnitude as well as the regional distribution of the response of the atmosphere–ocean system to an increase of atmospheric carbon dioxide concentrations [10,11] and that the thermal inertia of the ocean influences the time scale of the atmospheric response [12,13]. Ocean modelling was however in its infancy and the report outlined some of the key challenges as they were perceived at the time: ‘The main problems in ocean modelling arise from uncertainties in the parameterization of unresolved motions, from insufficient spatial resolution, and from poor estimates of air-sea fluxes’ [9, p. 121]. Elsewhere the report noted that ‘the explicit simulation of mixing by mesoscale eddies is feasible and highly desirable, but so far the computer capacity required for 100 year simulations of a coupled global eddy resolving ocean–atmosphere GCM has not been available’ [9, p. 179]. It is probably fair to say that many of these challenges outlined in 1990 are still broadly applicable today.

At the time of the first IPCC report, it was also recognized that to be considered a credible tool for the prediction of climate, ocean models needed to compare well with the observed ocean circulation and water mass distribution. However, in an era before the World Ocean Circulation Experiment had dramatically enhanced the database of ocean observations, the paucity of data limited the extent to which such comparisons could be made. Where it was possible to make comparisons, early coupled atmosphere–ocean models showed significant differences with respect to observations. Even when initialized with realistic initial conditions, models typically drifted over time to show warmer surface temperatures in the Southern Ocean compared with observations and cooler surface temperatures in the tropics and high northern latitudes. This failure of early coupled atmosphere–ocean models and their failure to properly represent the meridional overturning circulation (MOC) and other key aspects of the dynamics of the ocean are clearly evident from depth–latitude profiles of temperature and
salinity presented in figure 2. The signature of sinking dense water formed in the northern North Atlantic and around Antarctica is evident in the observed temperature and salinity profiles, but not in the simulated profiles. Similarly, the observations clearly show the equatorward spreading of low salinity Antarctic Intermediate Water (AAIW) along isopycnals in the Southern Hemisphere, but there is no corresponding feature in the simulated profiles. In addition, the simulated thermocline is not as intense as in observations. Attempts were made to forcibly remove such systematic errors by adjusting the surface fluxes [16,17], although this approach was always recognized to be unsatisfactory and highly unphysical. As described below, considerable advances have been made over the past 20 years in this respect, but we still have some way to go before we can claim that climate models are able to replicate all relevant aspects of the observed ocean.

In 1995, the Coupled Model Intercomparison Project (CMIP) was established to study and intercompare climate model simulations [18]. This initiative of the World Climate Research Programme has continued over the past 20 years as an invaluable means of coordinating and then assessing climate model simulations provided by the different modelling centres across the world, using model–observation and model–model comparisons. The origins of ocean model biases are not straightforward to identify—they can arise from the limitations or poor

Figure 2. Zonal mean (a) temperature and (b) salinity as simulated in a 30-year integration of an early coupled atmosphere–ocean model with an ocean resolution of 5° latitude–longitude and four layers [14], together with observations (c, d) from Levitus [15]. Adapted from [14, figs 12 and 13]; results also reported in [9].
formulation of any of the elements of the coupled model (numerical algorithms, grid resolution, subgrid-scale parametrizations, unrepresented components, etc.). Often it is difficult/impossible to identify the ‘cause’ simply by looking at the ‘symptom’. To make progress on this issue requires the application of ideas motivated by targeted observational studies or arising from the study of fundamental aspects of the underlying geophysical fluid dynamics. Observational and theoretical research are the engines of innovation for model development. In addition, complementary to the development of realistic climate models, there is an important role for simplified conceptual models, which have been used in many studies to gain an understanding of the key processes. This highlights the fact that it is essential that any long-term modelling strategy is underpinned by basic research—both observational and theoretical—and that the value fundamental research provides in this respect is recognized and championed.

3. Steps in progress to date

A significant advance in the development of ocean models for climate prediction over the past 20 years was the first simulation [19] of present day climate to be conducted without the need for flux corrections to prevent a drift of the surface temperatures. The steps to progress here are a clear example of the value of fundamental research. Twenty years ago, the ocean models used Laplacian diffusion in the horizontal and vertical directions as the closure for eddy terms, with the horizontal diffusivity coefficient typically $10^7$ times larger than the vertical. However, early observational studies had been interpreted to imply that mixing is much greater along rather than across isopycnal surfaces [20,21]; a model construct with a large horizontal diffusion was inconsistent with these and other observations [22,23]. Then, inspired by an idealized geophysical fluid dynamics study, Peter Gent and Jim McWilliams (GM) set about developing a more realistic parametrization of the effect of sub-grid mesoscale eddies for use in coarse-resolution models [24,25]. The GM parametrization can be viewed as representing baroclinic instability through an eddy-induced advection term which acts to flatten density surfaces [26]. A key feature of the parametrization is that it conserves the net volume of fluid contained between any two isopycnal surfaces and thus it avoids the spurious diapycnal water mass transformations that were introduced through previous horizontal diffusion terms. It led to significant improvements to the simulated ocean thermocline structure and meridional overturning [24,27,28] when implemented in models. Along with neutrally oriented downgradient diffusion schemes [23,29,30], GM provides the framework for nearly all mesoscale eddy parametrizations used in current climate models. Implementation of the GM parametrization, together with the K-profile parametrization for vertical mixing [31], and other refinements in the ocean and atmosphere (including improving the ocean resolution to allow the oceanic heat transport to be realistically simulated) led to the first no-flux-correction climate simulation [19].

By the time of the fourth IPCC assessment report [7] and the third Climate Model Intercomparison Project (CMIP3), the majority of climate models were run without flux corrections and they showed significant improvements in their representation of the surface mixed layer as a consequence of developments in...
mixing parametrizations. Nevertheless, there were still substantial differences in the model representation of ocean properties as compared with observations. Although the multi-model mean zonally averaged sea surface temperature (SST) error was less than 2°C at all latitudes, many of the CMIP3 models showed too cool SSTs in the northern mid-latitudes and too warm SSTs in the Southern Ocean (figure 3). In depth, the models typically showed a cold bias in the upper 200 m, and a warm bias at depths ranging from 200 to 3000 m (figure 4) with the maximum warm bias located in the region of the North Atlantic Deep Water (NADW) formation. The poor representation of diapycnal mixing in models may account for some of these biases [35]. Errors, for example, in the location of the maximum wind stress in the Southern Hemisphere were also thought to contribute to the biases via their influence on the water masses

3Thought to be a consequence of the path of the Gulf Stream–North Atlantic Current which along with other western boundary currents is poorly simulated in climate models [32].

Phil. Trans. R. Soc. A (2012)
of the Southern Ocean [36,37]. In broad terms, many of the CMIP3 models provided a reasonable simulation of Subantarctic Mode Water (SAMW) and AAIW, with some notable exceptions [38]. Nevertheless, overall the relatively poor Southern Ocean simulation in the models was a concern because it can influence the response to increased greenhouse gases by affecting the oceanic uptake of heat and carbon. The Southern Ocean is believed to act as a significant sink of carbon, accounting for about 40 per cent of the global oceanic uptake of anthropogenic CO$_2$ over the past two centuries [39,40]. The transport of the Antarctic Circumpolar Current (ACC) varied by an order of magnitude across models (from 37 to 337 Sv) and was found to correlate strongly with the value of diffusivity used for the GM parametrization [41]. Of concern also was the poor representation of the hydrography of the Labrador and Irminger Seas [42], where many of the constituents of NADW are either formed or adjusted, because these are important areas to simulate realistically in order to accurately represent global heat and freshwater transport. Perhaps, though, the greatest weakness of the CMIP3 models was found in their representation of sea ice. Since the earliest climate modelling studies, sea ice has been recognized as a critical feedback [43]. Assessment of Arctic sea ice in the CMIP3 models indicated very substantial differences between simulations and observation and considerable inter-model scatter [44–46]. In particular, the models underestimated [44] the strong decline in sea ice extent at the end of the summer melt season in September Arctic that had been observed over the satellite-data period (i.e. since 1979).
Around 20 years ago, the first eddy-permitting regional ocean models were introduced. Some model studies [47–50] focused on the dynamics of the Southern Ocean, including, for example, examining momentum and vorticity budgets, while others [51,52] were focused on the Atlantic and issues such as Gulf Stream separation. Since then, computing advances meant it became possible to conduct global ocean-only simulations at eddy-permitting resolution [53]. It is known that eddy processes are particularly important in the Southern Ocean since the lack of meridional boundaries means they must play a central role in the dynamics [54,55]. As noted above, understanding the sensitivity of the overturning circulation in the Southern Ocean is critical because of the associated implications for climate feedbacks: increases to the circulation would imply an increased upwelling of deep water rich in dissolved inorganic carbon south of the circumpolar flow, resulting in a reduction of Southern Ocean CO₂ net uptake relative to expectations from atmospheric CO₂ levels. There is considerable ambiguity concerning the present state with some observational and modelling studies indicating that the Southern Ocean uptake of anthropogenic CO₂ may be stalling [2,56] and others not [57,58]. Recent model simulations suggest that the future of the overturning circulation and carbon uptake depend sensitively on the dynamical response to surface wind forcing, which encompasses eddy processes [3,59–64].

In parallel to ocean and coupled-climate model development, idealized and conceptual modelling studies have progressed our understanding of some of the fundamental aspects of ocean dynamics, including coupled atmosphere–ocean processes. For example, it has become clear over the past 20 years that a key part of the overturning circulation of the ocean is the return path from the interior ocean to the surface through Southern Ocean upwelling driven by winds. This pathway has been elucidated through a combination of observational studies involving inverse methods and theoretical studies making use of residual-mean theory (see [65] for a review). Idealized models have been used to explore the dynamical connections responsible for setting, for example, the strength of the Antarctic Circumpolar Current [66–68] and a range of models of varying complexity have been used to examine possible bistability of the Atlantic MOC (AMOC) [16,69,70], following the original box-model study of Stommel [71]. A hierarchy of models has been used to study the remote ocean response to changes in the MOC at high latitudes [72–78]. These studies indicate that the initial adjustment occurs via the propagation of fast Kelvin waves along the western boundary to the equator, along the equator and poleward along the eastern boundary, and that this is followed by slower Rossby waves radiating from the eastern boundary into the ocean interior, providing a time scale for interdecadal variability [79]. Other studies have considered the coupled atmosphere–ocean response [80]. Theoretical studies and idealized models have also been used to examine the role of eddies in the Southern Ocean [81–84] and the influence of bottom topography [85,86]. As an example, figure 5 represents the results of a study [86] where a large-scale topographic slope with an arbitrary orientation was introduced into quasi-geostrophic, doubly periodic, barotropic and baroclinic systems. In both systems, the flow organizes itself into coherent tilted non-zonal jets which are aligned perpendicular to the barotropic potential vorticity (PV) gradient, with the interesting result that in the baroclinic system the jets cross layerwise PV gradients.
Figure 5. The tilting of the jets is associated with the changes in the PV structure caused by the introduction of a zonal gradient in bottom slope, $h_x$, to a quasi-geostrophic barotropic system. Plots show snapshots of the streamfunction with the jets aligned perpendicular to the barotropic PV gradient (adapted from [86], fig. 3a).

Over the past 20 years there has been a considerable focus on understanding, simulating and predicting the El Niño Southern Oscillation (ENSO)\(^4\) using models of varying complexity (see [88] for a review of the early studies and [89] for a review of recent progress and challenges), guided by and incorporating observations [90]. The simulation of ENSO by coupled climate models has improved significantly over recent years; however, the results of different models remain diverse owing to an incomplete understanding of ENSO dynamics and an inability of models to fully resolve or parametrize all the relevant processes [91]. In addition, since the year-to-year variability of ENSO is controlled by a delicate balance of amplifying and damping feedbacks each of which may be modified by climate change, predicting future change to ENSO activity is challenging [92].

A host of new observations have become available over the past 20 years. New measurements, for example from satellite altimetry, the Argo profiling drifter project, the Global Tropical Moored Buoy Array, and the continuous monitoring of the AMOC at 26.5\(^\circ\)N which is now providing estimates of the mean strength and variability [93], have provided valuable new data for use in theoretical analysis, parametrization development and model validation. As just one example, satellite altimetry data have been used in numerical studies to diagnose eddy mixing at the surface of the Southern Ocean, leading to a new understanding of the regional distribution of eddy diffusivity, its relationship with the mean flow and implications for air/sea fluxes [94–97]. A major advance has been the development of techniques to assimilate diverse observations into ocean models in order to produce a quantitative depiction of the time-evolving global ocean state [98–102] and also to investigate biogeochemical cycles [103]. This offers up the potential for a much closer synergy between observational and numerical studies. For example, analysis of a state estimate [104] has led to the hypothesis that there is a sub-surface maximum of eddy diffusivity in the Southern Ocean (figure 6), which has motivated new observational studies [105], further observational data analysis [106], and the development of an eddy diffusivity parametrization [107]. State estimates have also allowed for

\(^4\)ENSO is the dominant mode of interannual climate variability. It originates in the tropical Pacific and affects weather and climate patterns worldwide [87].
new assessments of coupled climate models. For example, one study [108] has estimated water mass transformation rates resulting from surface buoyancy fluxes and interior diapycnal fluxes in the region south of 30° S in a model-based state estimation and three free-running coupled climate models, finding for example that the meridional transport of deep and intermediate waters across 30° S agrees well between models and observationally based estimates in the Atlantic Ocean but not in the Indian and Pacific, where the model-based estimates are much smaller.

4. Current state and future direction

As we have seen, 20 years ago, the ocean component of climate models was very basic. Since then, increase in computing power has allowed higher vertical and horizontal model resolution, global observations have influenced the development of theory and models, and theoretical developments have enabled parametrizations to be implemented in models for some important processes. All of these have resulted in significant improvements to the veracity of ocean models. Nevertheless, computing power is still a limiting factor, significant mismatches between climate models and observations remain, known important processes remain poorly or not at all represented, and the understanding and modelling of interactions with other aspects of the Earth system remain primitive. Many of the simulations being conducted for the fifth IPCC report and the
Coupled Climate Model Intercomparison Project Phase 5 (CMIP5) have now been completed. Early analysis indicates that some aspects of the modelled ocean are in closer agreement with observations compared to CMIP3 (e.g. ACC transport [109]). The representation of Arctic sea ice has improved with respect to the CMIP3 models [110], although Antarctic sea ice is poorly represented with almost all models indicating recent trends in mean annual sea ice extent that are of the opposite sign to observations [111]. Improvements to the representation of ENSO have also been documented [112]. However, there remain significant differences in the model representation of many ocean properties. In the Southern Ocean, there are strong model–model and model–observations differences in the properties and distribution of water masses (figure 7) and there are strong differences in the maximum mixed layer depth (MLD) in some models compared with observations (figure 8).

Figure 7. Water-mass structure (see [113] for more details) superimposed on the zonal mean potential temperature structure (1976–2006) for CMIP5 models and observations [114] (bottom right panel). Contour lines indicate the boundary between (from surface to bottom): surface water, SAMW, AAIW, Circumpolar Deep Water and Antarctic Bottom Water.
A new focus of activity concerns decadal prediction, providing forecasts of time-evolving regional climate conditions over the next 10–30 years [117–119]. Building on the observation that much decadal climate variability arises from slow variations in the ocean circulation [120], several methods have been proposed for initializing global coupled climate models for decadal predictions which are based on initialization with aspects of the ocean state including temperature and salinity. These methods include: initializing with observations of atmospheric and ocean (surface and sub-surface) conditions [117]; using ocean data from a state estimate [118]; initializing only with SSTs and relying on ocean transport processes to initialize the sub-surface indirectly [119]; and using an ensemble of ocean-only model simulations forced by atmospheric reanalysis.
to generate an ocean initialization [121]. The different methods have provided different predictions and given the present paucity and sometimes poor quality of observational sub-surface ocean data it is not yet clear which approach will prove most reliable [121]. An experimental framework to address decadal predictability/prediction has been incorporated into the CMIP5 experiments [122]. Early analysis indicates high prediction skill for surface temperature over the Indian, North Atlantic and western Pacific Oceans and for the Atlantic Multidecadal Oscillation index, but low skill over the equatorial and north Pacific Ocean and for the Pacific Decadal Oscillation index [123].

A number of different research activities are in progress that may revolutionize ocean modelling over the coming decades. Unstructured meshes are frequently used in computational fluid dynamics and over recent years progress has been made in developing new ocean models based on finite volumes, finite elements and arbitrary Lagrangian–Eulerian methods. They offer the hope of better resolving some of the important dynamical processes (figure 9) as well as allowing improved representation of coastal boundaries and bottom topography [129], but their implementation comes at a considerable computational cost. Some of the issues that remain for these approaches to be used for ocean climate modelling, including the development of new tools for analysis of the models, are outlined in a recent review [130]. In another direction, stochastic parametrizations are being developed for climate models. It is argued that these parametrizations are more consistent with the underlying equations of motion, and provide more skilful estimates of uncertainty when compared with estimates from traditional multi-model ensembles, on time scales where verification data exist [131]. It has also been suggested that there may be an opportunity to develop stochastic dynamical cores for climate models taking advantage of stochastic processing hardware (see [131] for more details). Finally, to more accurately simulate sea level as well as bottom pressure, new climate models during the next decade may need to be based on non-Boussineq equations [130].

Increases in computing power are now enabling the ocean components of coupled models to be run at higher resolution, resolving more of key dynamics [132]. However, even as improved computing resources allow mesoscale eddies to be resolved in the coupled atmosphere–ocean–ice models used for centennial climate projections, it may not be feasible to explicitly resolve them in more comprehensive models such as those including biogeochemical processes. Thus, the question of how best to specify the eddy diffusivity for parametrizations is likely to remain for the foreseeable future. Moreover, with increased model resolution there may be a need to pay closer attention to how to account for the effects of mesoscale eddies that are perhaps only partially resolved. Indeed, with limited resources (both in terms of computational power and human capacity), it is by no means obvious how the balance should be struck between focusing efforts on high-resolution modelling, the development of more sophisticated parametrizations, the use of statistical approaches such as running ensemble simulations, and the inclusion of more components of the Earth system. This question has always generated lively debate in the community and will no doubt continue to do so. Recent efforts to develop high-resolution climate models [133] have demonstrated that although high resolution can provide substantial benefits for some aspects of the climate system and its variability, some significant model problems remain and new ones can emerge; thus high resolution alone is not
Figure 9. Diagnosed absolute vorticity with contours of streamfunction for barotropic flow past a cylinder on a beta-plane simulated using Fluidity-ICOM, an unstructured mesh finite element model [124–126]: (a) low boundary mesh resolution simulation presenting a two-jet structure in the lee of the cylinder [127] and (b) high boundary mesh resolution simulation presenting an intense one-jet structure (adapted from [128]).

a panacea for all climate model errors. Moreover, it is not clear which aspects of the ocean are essential to accurately represent for climate prediction and which are less important. Some studies have suggested that a coupled model’s atmospheric climatology and transient response to increased greenhouse gases may not be very sensitive to some aspects of the representation of the interior ocean [134,135]; gaining a better understanding of this is likely to be an area of significant future research.

Recent developments in eddy parametrization include, for example, a new framework for parametrizing eddy fluxes of PV [136]. This framework has the potential to more directly address issues such as eddy mean flow interactions and the overall energetics of the ocean system than traditional parametrizations such as GM. There is also an increasing focus of research activity on submesoscale
eddy and fronts [137–139]. These manifest themselves as lateral density gradients and intense circulations throughout the upper ocean over spatial scales of 1–10 km and are potentially a leading order process within the surface mixed layer. The first parametrizations of their role in restratifying the mixed layer are now being implemented in models [140]. Targeted observations and further theoretical work are needed to further develop and validate these parametrizations. Efforts are also being made to improve the parametrization of turbulent mixing in the ocean surface boundary layer to include surface wave effects such as mixing by breaking waves and Langmuir turbulence [141]. In addition, parametrizations for deep convection and entrainment as water flows over ocean ridges or down continental slopes, which determine the properties and quantity of deep water, are being developed and implemented [142] following theoretical/basic research [143]. Turbulent diapycnal mixing is represented in many present generation climate models with a simplistic diffusivity below the surface mixed layer. However, the last 20 years of ocean mixing research have instead revealed dramatic spatial and temporal heterogeneity in diapycnal mixing, which can arise from processes such as gravity wave breaking. The modelling and observational developments required to make progress in this area have been discussed in recent White Papers for Ocean Obs 09 [130,144]. In summary, it is probable that there will remain a considerable focus on developing new parametrizations to represent more of the processes that are known to play a key role in determining climatically important aspects of the ocean dynamics such as the global MOC and the properties of the surface mixed layer over the coming years.

New questions and challenges are likely to arise at the interface of oceanography and other components of the Earth system. The role of ocean mesoscale eddies in mediating the response of biogeochemical cycles to changed forcings, for example, is already being studied [63] and is likely to remain a significant area of research. The availability of three-dimensional observationally based data from state estimates will allow us to address questions which have previously been beyond reach such as, for example, where are the primary mode and intermediate water export pathways out of the Southern Ocean, how do they affect anthropogenic carbon sequestration and what are the physical processes that set the location and intensity of the pathways? Progress on understanding and modelling aspects of the coupling between the atmosphere, ocean and ice is also probable and will require theoretical advances, new observational data and model development. For example, recent modelling and observational studies have indicated that basal melting from contact with a changing ocean is the primary control of Antarctic ice-sheet loss and have highlighted the need to consider oceanic effects in the future evolution of ice sheets [145,146]. With this in mind, work is now commencing to couple ice-sheet and ocean components of climate models.

Basic questions concerning the Earth system, such as what sets the pole–equator temperature gradient and the extent of the polar icecaps, are still not fully understood. Recent work addressing these questions has included consideration of idealized aqua-planet models [147,148], serving as a reminder that in the drive for ever more realistic Earth system models, simplified models can still provide valuable insight into the fundamental mechanisms. As another example of this, a recent study [149] has used an idealized process model (figure 10) to investigate the newly discovered North Icelandic Jet, which is estimated to supply...
half the total Denmark Strait overflow, contrary to the prevailing wisdom that primary source of overflow water (and hence water for the lower limb of the AMOC) is the East Greenland Current. The modelling suggested that import of warm, salty water from the North Icelandic Irminger Current and water mass transformation in the interior Iceland Sea are critical to the formation of the jet with implications for the sensitivity of the system to climate change.

5. Discussion

It is impossible in one article to review all the potential pathways for future progress in ocean modelling. It is also impossible to accurately predict where scientific breakthroughs may occur. The review of the past 20 years has indicated that we might reasonably expect significant advances in some areas over the next 20 years and equally to find ourselves still grappling with some of the same issues. However, in broad terms, it seems that there are likely to be three main avenues of future research activity. The first involves addressing coupled problems concerning the changing ocean, atmosphere, cryosphere and biosphere. The challenge of understanding and predicting the changes to the Earth system we may be inducing by emissions of greenhouse gases and other radiatively active species (including those manifested as a consequence of ocean acidification) will surely remain paramount. More generally, there is likely to be a need to provide answers to tough questions about the system’s response to environmental stresses (and to manage expectations since some questions posed to us may not be possible to answer with confidence). The second involves operationalizing ocean modelling. In the future, ocean models and their output are likely to be used by an increasing number of actors interested in problems from coastal fisheries to storm...
surge prediction [150]. Data assimilation will become increasingly important, both for decadal forecasting systems and for providing the ocean equivalent of atmospheric reanalysis datasets. The initial results of ocean state estimates are already providing an invaluable resource, magnifying many times the value of inherently spatially and temporally inhomogeneous observations; it would seem wise to invest in the skills required to further develop this approach, which could also be used to help design new observation systems [151]. The third involves continuing to establish the basic principles of ocean dynamics upon which applied research must be based. The developments we have seen in climate modelling over the past 20 years would have been impossible without significant advances in computing technology. However, the review of the past 20 years has clearly demonstrated the crucial role of fundamental theoretical and observational research in ocean model development and in advancing our understanding of the climate system.

Oceanographers involved in climate modelling and prediction will need to respond over the next 20 years to a range of pressing questions. How will regional climate patterns alter over the coming years and decades? What is the risk of sudden, dramatic or irreversible climate change? What changes will we see in climate-driven variables of particular societal or commercial importance (for example to inform adaptation strategies)? And how will climate change interact with broader environmental stresses, such as disease incidence, energy supply, and food and water security? The scientific priorities likely to emerge in our efforts to answer these questions include the following: (i) improved characterization of risk for external audiences via better identification, quantification and reduction of scientific uncertainties; (ii) improved understanding of nonlinear aspects of the climate system; (iii) a greater focus on understanding and predicting climate variability, including on decadal time scales; (iv) optimally designed observational and monitoring networks; (v) an enhanced emphasis on interdisciplinary studies; and (vi) coupling an ongoing need for underlying basic research with greater focus on its application. One of the challenges that this will raise is how best to provide a conduit for effective engagement between the stakeholders (‘users’) and the scientific researchers (‘producers’). There will be a need to translate fluently between the language of the producers and the users, to identify and synthesize the research results of relevance to users and to flag to producers the priority needs of users, and to facilitate discussions between users and producers so each gains a better understanding of what is desired and what is possible in terms of the provision of scientific evidence for decision-making.

As outlined above, a number of scientific activities are already being undertaken that will help address the questions that will be asked of the ocean modelling community in the future: measurements and process studies are being conducted or are planned to look as aspects such as submesoscale dynamics, biogeochemistry responses and air–sea interactions; new measuring opportunities, for example from gliders, seismics, deep Argo floats and under-ice technologies, are becoming available; and innovative approaches using developments in computing such as unstructured grids, and even novel hardware technologies, are being considered. New scientific advances will be required; for example, the further development of data assimilation and state estimation as discussed above, the introduction of operational models for societal and commercial needs, and the on-going development of modelling approaches applied to both short
(decadal) and long (palaeoclimate) time scales. In addition, research activities will need to be underpinned by a robust infrastructure: there will be a need for enhanced technical and engineering support for modelling and data management, interdisciplinary activities will require appropriate training and facilitation of collaborative engagements, and increased efforts will need to be made to exchange knowledge effectively and efficiently between research scientists and end-users.

As ocean modelling reaches a new level of maturity, the challenges remain substantial, but the opportunities to make a significant impact in the realm of climate prediction are great.

I am grateful to the organizing committee of ‘Prospectus for UK Marine Science for the Next 20 Years’ Joint Project (Harry Bryden, Gwyn Griffiths, Carol Robinson and Terry Sloane) for arranging the discussion meeting and soliciting this paper. I thank Alistair Adcroft and an anonymous reviewer for their helpful comments and David Marshall for additional advice.

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