PROBLEMS AND PROSPECTS IN LARGE-SCALE OCEAN CIRCULATION MODELS

S.M. Griffies(1), A.J. Adcroft(2), H. Banks(3), C. W. Böning(4), E.P. Chassignet(5), G. Danabasoglu(6), S. Danilov(7), E. Deleersnijder(8), H. Drange(9), M. England(10), B. Fox-Kemper(11), R. Gerdes(12), A. Gnanadesikan(1), R.J. Greatbatch(4), R.W. Hallberg(1), E. Hanert(13), M.J. Harrison(1), S. Legg(2), C.M. Little(14), G. Madec(15), S.J. Marsland(16), M. Nikurashin(2), A. Pirani(17), H.L. Simmons(18), J. Schröter(7), B.L. Samuels(1), A.-M. Treguier(19), J.R. Toggweiler(1), H. Tsujino(20), G.K. Vallis(2), L. White(21)

(1) NOAA (National Oceanic and Atmospheric Administration)/Geophysical Fluid Dynamics Laboratory, 201 Forrestal Road, Princeton, NJ 08542, USA. Email: Stephen.Griffies@noaa.gov; Anand.Gnanadesikan@noaa.gov; Robert.Hallberg@noaa.gov; Matthew.Harrison@noaa.gov; Bonnie.Samuels@noaa.gov; Robbie.Toggweiler@noaa.gov

(2) Princeton University and NOAA/GFDL (National Ocean and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory), 201 Forrestal Road, Princeton, NJ 08542, USA. Email: Alistair.Adcroft@noaa.gov; Sonya.Legg@noaa.gov; Maxim.Nikurashin@noaa.gov; Geoffrey.Vallis@noaa.gov

(3) UK Met Office, Hadley Centre, FitzRoy Road Exeter, Devon EX1 3PB United Kingdom. Email: helene.banks@metoffice.gov.uk

(4) Leibniz-Institut für *Meereswissenschaften/Leibniz Institute of Marine Sciences, IFM-GEOMAR (Research Center for Marine Geosciences), Dienstgebäude Westufer Düsternbrooker Weg 20, D-24105 Kiel, Germany. Email: cboening@ifm-geomar.de; rgreatbatch@ifm-geomar.de*

(5) Center for Ocean-Atmospheric Prediction Studies (COAPS), Florida State University, 2035 E. Paul Dirac Drive 200 R.M. Johnson Building, PO Box 3062840, Tallahassee, FL, 32306-2840, USA. Email: echassignet@coaps.fsu.edu

(6) National Center for Atmospheric Research, Climate and Global Dynamics Division, P.O. Box 3000, Boulder, CO 80307-3000, USA. Email: gokhan@ucar.edu

(7) Alfred Wegener Institut für Polar- und Meeresforschung, Bussestr. 24, 27570 Bremerhaven, Germany. Email: sdanilov@awi-bremerhaven.de; Jens.Schroeter@awi.de

(8) Université Catholique de Louvain (UCL), Centre for Systems Engineering and Applied Mechanics (CESAME), 4 Avenue G. Lemaître, 1348 Louvain-la-Neuve, Belgium. Email: eric.deleersnijder@uclouvain.be

(9) Department of Geophysics, University of Bergen, Allegt. 70, 5007 Bergen, Norway. Email: helge.drange@nersc.no

(10) Climate Change Research Centre (CCRC), Faculty of Science, The University of New South Wales, Sydney, New South Wales 2052, Australia. Email: M.England@unsw.edu.au

(11) University of Colorado at Boulder, CIRES Bldg., Rm. 318, Attn: Fox-Kemper, 216 UCB, Boulder, CO 80309-0216, USA. Email: bfk@colorado.edu

(12) Climate Sciences, Alfred Wegener Institut für Polar- und Meeresforschung, Bussestr. 24, 27570 Bremerhaven, Germany. Email: Ruediger.Gerdes@awi.de

(13) Department of Environmental Sciences and Land Use Planning Faculty of Bioengineering, Agronomy and Environment, Université Catholique de Louvain, Place Croix du Sud 2/16, B-1348 Louvain-la-Neuve, Belgium. Email: emmanuel.hanert@uclouvain.be

(14) Princeton University Geosciences Program, 201 Forrestal Road, Princeton, NJ 08542, USA, Email: cmlittle@Princeton.edu

(15) Laboratoire d'Océanographie et du Climat, CNRS-UPMC-IRD (Centre National de la Recherche Scientifique-Université Pierre et Marie Curie-Institut de Recherches pour le Développement), 43 rue Cuvier, 75231 Paris Cedex 05, France, and National Oceanography Centre, University of Southampton, Waterfront Campus, European Way, Southampton SO14 3ZH, United Kingdom, Email: Gurvan.Madec@lodyc.jussieu.fr

(16) The Centre for Australian Weather and Climate Research, Private Bag 1, Aspendale, VIC 3195, Australia. Email: Simon.Marsland@csiro.au

(17) International CLIVAR (Climate Variability and Predictability) Project Office, Southamptom, UK, and Princeton University AOS (Atmospheric and Oceanic Sciences) Program, 300 Forrestal Road, Sayre Hall, Princeton, NJ 08544, Email: anna.pirani@noc ac.uk

(18) International Arctic Research Center, 930 Koyukuk Drive, P.O. Box 757340, Fairbanks, Alaska 99775-7340, USA. Email: hsimmons@iarc.uaf.edu

[19] *Laboratoire de Physique des Océans, UMR (Unités Mixtes de Recherche) 6523 CNRS-IFREMER-IRD-UBO (Centre National de la Recherche Scientifique-French Research Institute for Exploration of the Sea/Institut Français de Recherche pour l'Exploitation de la Mer-Institut de Recherches pour le Développement-University of Western Brittany), IUEM (European Institute for Marine Studies/Institut Universitaire Européen de la Mer), IFREMER (French Research Institute for Exploration of the Sea/Institut Français de Recherche pour l'Exploitation de la Mer), BP 70, 29280 Plouzané, France. Email: Anne.Marie.Treguier@ifremer.fr*

[20] *Japan Meteorological Agency/Meteorological Research Institute, Nagamine 1-1, Tsukuba, Ibaraki 305-0052, Japan. Email: htsujino@mri-jma.go.jp*

[21]*ExxonMobil Research and Engineering, 1545 Route 22 East Room LD350, Annandale, NJ 08801 USA, Email: laurent.white@exxonmobil.com*

ABSTRACT

We overview problems and prospects in ocean circulation models, with emphasis on certain developments aiming to enhance the physical integrity and flexibility of large-scale models used to study global climate. We also consider elements of observational measures rendering information to help evaluate simulations and to guide development priorities.

1. SCOPE OF THIS PAPER

Numerical ocean circulation models support oceanography and climate science by providing tools to mechanistically interpret ocean observations, to experimentally investigate hypotheses for ocean phenomena, to consider future scenarios such as those associated with human-induced climate warming, and to forecast ocean conditions on weekly to decadal time scales using dynamical modeling systems. We anticipate that the already significant role models play in ocean and climate science will increase in prominence as models improve, observational datasets grow, and the impacts of climate change become more tangible.

The OceanObs'09 Conference focused on developing a framework for designing and sustaining world ocean observing and information systems that support societal needs concerning ocean weather, climate, ecosystems, carbon and chemistry. Many of the Community White Papers contributed to OceanObs'09 directly discuss topics where ocean models play a central role in generating information, in conjunction with observations, appropriate for ocean forecasting/prediction, state estimation, data assimilation, sensitivity analysis, and other forms of ocean information on both short (days) and long (decades to centuries) time scales ([1–9]). The central purpose of the present paper is to highlight important research that forms the scientific basis for ocean circulation models and their continued evolution. We provide examples and recommendations where observations support the evolution of ocean models. The above listed White Papers, those from [10] and [11], and others, provide further discussions and recommendations of measurements that support the development and use of ocean models.

2. OCEAN MODELS AND MODELING

The ocean is a forced-dissipative system, with forcing largely at the boundaries and dissipation at the molecular scale. It is contained by complex land-sea boundaries with motions also constrained by rotation and stratification. Flow exhibits boundary currents, large-scale gyres and jets, boundary layers, linear and nonlinear waves, and quasi-geostrophic and three-dimensional turbulence. Water mass tracer properties are preserved over thousands of mesoscale eddy turnover time scales. These characteristics of the ocean circulation pose significant difficulties for simulations. Indeed, ocean climate modeling is an application of a very different nature to those found in other areas of computational fluid dynamics (CFD). The time-scales of interest are decades to millennia, yet simulations require resolution or parameterization of phenomena whose time scales are minutes to hours. Furthermore, the most energetic spatial scales are of order 10 km-100 km (mesoscale eddies), yet the problem is fundamentally global in nature. There is no obvious place where grid resolution is unimportant, and computational costs have strongly limited the use of novel, but often more expensive, numerical methods.

These features of the ocean climate modeling problem present difficult barriers for methods successfully implemented in other areas of CFD. Consequently, ocean climate models predominantly use structured meshes and grid-point methods associated with finite differences [12]. These methods are efficient and familiar, benefitting from decades of research experience. As discussed in the following, much progress has been made towards incorporating new and more accurate algorithms for time stepping, spatial discretization, transport, and subgrid scale parameterizations ([13] provide an earlier review). We anticipate that structured mesh models will continue to be the predominant choice for ocean climate modeling for at least another decade. Nevertheless, significant progress has been made in new ocean models based on finite volumes, finite elements, and Arbitrary Lagrangian-Eulerian (ALE) methods.

The purpose of this document is to review ongoing scientific problems and prospects in ocean circulation models used to study global climate. We focus on the ocean model as a component of global climate models, noting that climate models are increasingly being used to study not only the climate system but also ocean dynamics. We offer suggestions for promising pathways towards improving simulations; provide hypotheses for how ocean climate models will develop in 10-20 years; and suggest how future models will help address important climate questions. The reference list, which focuses on work completed within the past decade, highlights the extensive research of relevance to ocean climate modeling.

Throughout this paper, we highlight the strong coupling of model evolution to information obtained from observations. To support this evolution, the climate modeling and observational communities must assess where observations and models diverge, and develop methodologies to resolve differences. This difficult task will continue to form the basis for the maturation of both model simulations and observational methods.

3. EQUATIONS OF OCEAN MODELS

The equations governing ocean circulation are based on Newtonian mechanics and irreversible thermodynamics applied to a continuum fluid. Conservation of heat and material constituents comprises a suite of scalar equations solved along with the dynamical equations. Though straightforward to formulate (e.g. [14]), the equations are difficult to solve, largely due to the nonlinear nature of the flow, and the very long timescales (decades to centuries) over which watermass properties are preserved in the ocean interior. These difficulties promote the use of numerical models to explore the immense phase space of solutions.

There are two main reasons why it is impractical to solve the unapproximated dynamical equations (Navier-Stokes equations) for climate simulations. First, ocean circulation exhibits extremely high Reynolds number flows, with dominant length scales of mesoscale eddy features many orders of magnitude larger than the millimeter scales where energy is dissipated. Second, the equations permit acoustic modes, whose characteristic speeds of order 1500m/s require an unacceptably small time step to resolve. The scale problem is normally handled by Reynolds averaging, which constitutes a filtering to partition the ocean state into resolved and unresolved subgrid-scale (SGS) components. The averaging scale is de facto imposed by the model grid. Correlations of SGS components lead to Reynolds averaged eddy-fluxes. These fluxes must be parameterized in terms of resolved fields (the closure problem). It is notable that the form of fluxes depends on the vertical coordinate chosen to represent the flow (Sect. 5), and the method of averaging (Sect. 6).

Currently, there are two approximations that independently filter out acoustic modes. The non-divergence approximation (associated with Boussinesq fluids) removes three-dimensional acoustic waves; the hydrostatic balance removes vertical acoustic waves. A third approach – filtering some wave types by implicit integration to allow longer time steps – is in development [15]. All large-scale regional and global climate models are hydrostatic, since these models do not resolve scales (smaller than a few kilometers) where non-hydrostatic effects become important [16–18]. It is thus unlikely that we will routinely see non-hydrostatic global ocean climate models for at least 10-20 years.

The volume conserving kinematics employed by Boussinesq fluids handicap prognostic simulations of sea level due to the absence of steric effects [19]. However, hydrostatic primitive equations written in pressure coordinates, which are non-Boussinesq and thus conserve mass, are algorithmically similar to Boussinesq geopotential coordinate models [20–23]. Hence, to more accurately simulate sea level, as well as bottom pressure, new ocean climate models during the next decade will be based on non-Boussinesq equations. Ironically, in situ observations are measured at pressure levels, and then typically interpolated to depth for gridded datasets. For pressure-based ocean models, the gridded data has to then be re-interpolated to pressure levels. We suggest that future observational data would better serve the ocean modeling community if it remained on pressure surfaces.

There are numerous questions that arise when discretizing the ocean equations, such as how to respect certain of the symmetries and conservation properties of the continuous equations on the discrete lattice (e.g. [24 and 25]). One issue that we emphasize here concerns conservation of scalar fields, such as mass and tracer. Tracer conservation and consistency with mass conservation require careful treatment of space and time discretization, especially when the spatial grid is time-varying ([26–31]). Ocean codes that fail to respect these properties are severely handicapped for use in ocean climate studies.

4. THE HORIZONTAL GRID MESH

Finite volume and finite elements have become common in certain areas of ocean modeling during the past decade. These methods provide generalization of gridding, and can be applied on both structured and unstructured meshes. We present here issues that must be resolved for their use in ocean climate modeling.

Finite volume methods (e.g. [32 and 33]) are appealing because cellwise conservation is built into the formulation, with discrete equations arising from integration of continuum equations over a grid cell. Ideas from finite volumes have been incorporated into certain ocean climate models (e.g. [34–37]). Particularly novel approaches include cubed sphere meshes [38], icosahedral meshes [39–42], and other approaches such as [43 and 44], each of which allow grid cells to be reasonably isotropic over the sphere. Successful examples of finite-volume models formulated on unstructured triangular meshes are given by [45] and [46].

Finite elements and finite volumes support numerous grid topologies inside the same model, and this feature allows for representation of the multiple scales of land-sea geometry, including the ocean bottom. Structured meshes provide analogous facilities, through non-standard orthogonal meshes [47] or nesting regions of refined resolution [48]. However, the unstructured approach is much more flexible [49]. Whereas each cell in a structured grid has the same number of neighboring cells, unstructured meshes can have different neighbors, thus facilitating resolution refinements. The discontinuous Galerkin method [50–54] compromises between continuous finite elements (e.g. unlimited choice of high-order polynomials) and finite volumes (for local scalar conservation in terms of fluxes across element boundaries, and a large inventory of flux limiters for advection operators). While coastal and estuarine unstructured-mesh models are commonly used [45, 46, 55–58], they are uncommon in ocean climate modeling [59 and 60], with [61] pioneering a realistic global example. We summarize issues that have been addressed recently, or require further research, in order to commonly realize robust unstructured mesh ocean climate models.

- **Staggering and geostrophy:** Traditional two-dimensional finite element pairs perform poorly when simulating ocean flows dominated by geostrophy. Research has helped identify acceptable elements for ocean modeling [62–67], with some staggerings analogous to structured finite difference Arakawa C- and CD-grids.
- **Advective transport:** Traditional finite elements are designed for elliptic problems, and hence are ill-suited for advection-dominated oceanographic flows and waves. However, semi-Lagrangian methods, discontinuous or nonconforming finite elements [53, 68–72], and discontinuous Galerkin methods have led to useful advection schemes for waves [73–78]. Spurious diapycnal mixing originating from numerical advection also remains an issue (Sect. 5.4), with consequences of variable resolution and dynamical meshes largely unexplored. The implementation of high-order advection schemes is natural for high-order discontinuous finite elements, but requires additional efforts in other cases.
- **Resolution-dependent physics:** Largely unexplored areas of research involve the matching of eddy-resolving regions with eddy parameterizations in coarse mesh regions, and the local scaling of viscosity and diffusivity coefficients.
- **Representation of bathymetry:** The ocean floor should be represented continuously across finely resolved mesh regions to faithfully simulate topographically influenced flows. This property is routinely achieved with terrain following vertical coordinates (Sect. 5.2), yet optimal strategies for unstructured mesh models remain under investigation.
- **Analysis:** New tools are required to analyze unstructured mesh simulations [79 and 80]. The immaturity of such tools handicaps traditional oceanographic analysis (e.g. transports, water mass properties) of unstructured mesh simulations.
- **Computational expense:** Low-order finite element models are about an order of magnitude more expensive than finite difference models, per degree of freedom [81]. Discontinuous finite elements suggest higher accuracy but are even less efficient numerically. Finite volumes [46] promise better efficiency and may serve as a good alternative. In all cases, optimization is essential in ocean climate models, with [54] presenting a potentially useful method.

Largely due to the issues noted above, and the potential for further undiscovered difficulties, the challenges ahead for unstructured grid ocean climate models are significant. Nonetheless, climate relevant simulations performed with unstructured grid codes are just now appearing [61], and we anticipate a coupled climate model using an unstructured mesh ocean to follow within a decade.

5. PARTITIONING THE VERTICAL

There are three traditional approaches to vertical coordinates: depth/geopotential; terrain-following; and potential density (isopycnic). Considerations include the following:

- Can the pressure gradient be easily and accurately calculated?
- Will material changes in tracers be large or small relative to SGS (sub-grid-scale) processes?
- Will resolution need to be concentrated in particular regions?
- How well does the vertical coordinate facilitate comparison to observations?

There is no optimal vertical coordinate for all applications, thus motivating research into generalized/hybrid approaches. We highlight here features of vertical coordinate choices, with [13] presenting more detail.

5.1 Z-coordinate models

Geopotential (z-) coordinate models have found widespread use in climate applications for several reasons, such as their simplicity and straightforward nature of parameterizing the surface boundary layer. Of the 25 coupled climate models contributing to the IPCC AR4 (Intergovernmental Panel on Climate Change Fourth Assessment Report) [82], 22 employ geopotential ocean models (one is terrain-following, one is isopycnal, and one is hybrid). Decades of experience and continued improvements with numerical methods, parameterizations, and applications suggest that geopotential models will remain the most common ocean climate modeling choice for the next decade.
There are three shortcomings ascribed to z-coordinate ocean models.

- Z-coordinate models can misrepresent the effects of topography on the large-scale ocean circulation. However, this problem is ameliorated by partial or shaved cells now commonly used [34, 35 and 83]. It is further reduced by the use of a momentum advection scheme conserving both energy and enstrophy, and by reducing near-bottom sidewall friction [84 and 85].
- Mesoscale eddying models can exhibit numerical diapycnal diffusion far larger than is observed [86 and 87]. Progress has been made to rectify this problem through improvements to tracer advection schemes, but further work is needed to quantify these advances.
- Downslope flows in z-models tend to possess excessive entrainment [88 and 89], and this behaviour compromises simulations of deep water masses derived from dense overflows. Despite much effort and progress [90–97], the representation/parameterization of overflows remains difficult at horizontal resolutions
- Coarser than a few kilometers [98].

5.2 Terrain following models

Terrain-following coordinate models (TFCM) have found extensive use for coastal applications, where bottom boundary layers and topography are well-resolved. As with geopotential models, TFCMs generally suffer from spurious diapycnal mixing due to problems with numerical advection [99]. Also, the formulation of neutral diffusion [100] and eddy-induced advection [101] has yet to be documented in the literature for TFCMs. Their most well known problem is calculation of the horizontal pressure gradient, with errors a function of topographic slope and near-bottom stratification [102–105]. The pressure gradient problem suggests that TFCMs will not be useful for global-scale climate studies, with realistic topography, until horizontal resolution is very fine (order 10km). For example, topography downstream of the Denmark Strait, along with bottom boundary layer thicknesses of order 200m, may require horizontal resolutions no coarser than 10km to study formation of North Atlantic Deep Water in TFCMs.

5.3 Isopycnal layered and hybrid models

Isopycnal models are inherently adiabatic when using a linear equation of state, and accept steep topography. They generally perform well in the ocean interior, where flow is dominated by quasi-adiabatic dynamics, as well as in the representation/parameterization of dense overflows [98]. Their key liability is that resolution is limited in weakly stratified water columns. For ocean climate simulations, isopycnal models attach a non-isopycnal surface region to describe the surface boundary layer. Progress has been made with such bulk mixed layer schemes, so that Ekman driven restratification and diurnal cycling are now well simulated [106]. We present here an update (relative to [13]) of efforts toward the use of isopycnal, and related hybrid, models for ocean climate modeling. Isopycnal and hybrid models are now viable for global climate applications; their use will likely become more widespread during the next decade.

- Potential density with respect to surface pressure (_0) has large-scale inversions in much of the ocean (e.g. Antarctic Bottom Water has a lower potential density with respect to surface pressure than North Atlantic Deep Water). However, _2000 is monotonically increasing with depth, except in some weakly stratified high-latitude haloclines [107]. As the vertical coordinate used by an ocean model must be a monotonic function of depth, _2000 is now widely used as the vertical coordinate in isopycnal models [108].

- For accuracy, all dynamical effects (e.g. pressure gradients) must be based on the in situ density rather than remotely referenced potential density [108]. Further works from [109] and [36] show how to avoid certain numerical instabilities associated with thermobaricity.
- If potential temperature and salinity are advected, cabbeling and double diffusion can lead to changes in potential density and a drift away from the pre-defined coordinate surfaces. [110] proposes two means to address this issue, but the methods compromise conservation of heat and/or salt, and are thus unacceptable for climate modeling. The density drift due to cabbeling or double diffusion is often smaller than from diapycnal mixing, in which case accurately tracking the coordinate density is straightforward [111]. However, especially in the Southern Ocean, cabbeling and thermobaricity can be of leading order importance [112 and 113]. These more general situations thus require accurate remapping without introducing spurious extrema or large diapycnal mixing [114].
- In contrast to geopotential coordinate models [115], isopycnal models do not rotate the diffusion tensor into the local neutral direction. Instead, they rely on the relatively close approximation of their coordinate surfaces to neutral directions. This assumption is less problematic than mixing along terrain-following surfaces or geopotentials, in particular since _2000 surfaces are impervious to adiabatic advection. But, it is unclear whether approximating neutral surfaces by _2000 surfaces is generally acceptable for climate simulations [107].
- The continuity equation (thickness equation) is prognostic in isopycnal models, and the resulting layer thickness must remain non-negative. This feature introduces complexities (particularly in the consistency and stability of the baroclinic-barotropic splitting) absent in z-coordinate and TFCMs [116]. Substantial progress has been made, but this remains an active research area.

Hybrid models offer a means to eliminate liabilities of the various traditional vertical coordinate classes. HYCOM (HYbrid Coordinate Ocean Model) [117–119] is the first community model exploiting elements of the hybrid approach, making use of the Arbitrary Lagrangian-Eulerian (ALE) method for vertical remapping [120]. Many numerical issues arising in HYCOM are similar to those found in its isopycnal coordinate predecessor, MICOM (Miami Isopycnic Coordinate Ocean Model) [121]. Yet there are improvements in HYCOM in the surface boundary layer and in shallow (and weakly stratified) marginal seas. However, placement of the vertical coordinates remains somewhat arbitrary, and the enforcement of this coordinate by remapping requires very accurate schemes to avoid excessive spurious diffusion.

5.4 The spurious diapycnal mixing problem

In the ocean interior, processes are largely constrained to be aligned with neutral directions [122], with observations from [123] establishing that anisotropy in eddy tracer diffusivities is roughly 108; i.e., dianeutral diffusivity is roughly 10□5m2=sec. Furthermore, theory [124] and observations [125] suggest even smaller values (10□6m2=sec; barely 10 times larger than molecular diffusivity) are present near the equator. As quantified by [86], these diffusivities are far smaller than levels of spurious numerical mixing present in most ocean climate models, especially those with mesoscale eddies. How important is it to respect the observed mixing in simulations? One suggestion comes from [126], who used an isopycnal ocean model, with spurious mixing below physical mixing levels. They demonstrated climate sensitivity (e.g. heat uptake) in the Pacific to parameterization of the equatorial mixing proposed by [124]. Further research is needed with such models to identify if other aspects of the general circulation require such small levels of diffusion.

6. SUBGRID SCALE PARAMETERIZATIONS

A successful parameterization is the result of understanding realized through observations, laboratory experiments, theoretical analysis, fine scale process simulations, and realistic simulations. We now briefly highlight research areas that have impacted, or will impact, ocean climate models.

6.1 Diapycnal processes

Parameterizations such as [106, 127–137] form the basis of the ocean surface layer in climate simulations, and likely will continue as long as models remain hydrostatic. In addition, there are efforts to couple surface wave effects such as mixing by breaking and Langmuir turbulence, and surface wave energy absorption [138–140]. Observations and large-eddy simulations of these processes are crucial to the development of these parameterizations [141–146].

The representation of topography and the degree of spurious numerical entrainment affect overflow and bottom boundary layer parameterizations. Level coordinate models are handicapped due to the excessive spurious entrainment [88 and 89], with methods focused on enhancing pathways available for flow [90–97]. TFCMs are well suited for overflows, with upper ocean turbulence closures often applied near the bottom. Isopycnal models also present a useful framework, since density layers are well suited for capturing the fronts present near overflows [111, 147 and 148]. References [149 and 150] review the state-of-science in representing and parameterizing dense overflows in simulations.

Interior diapycnal mixing occurs where internal gravity waves break, with the distribution of such regions very inhomogeneous in space and time [151 and 152]. Much energy for these waves is generated by tides scattering from the bottom [153–156], by geostrophic motions dissipating through generation and radiation of gravity waves from small-scale topography [157–160], and loss of balance arising from baroclinic instability [161]. Parameterizations such as [162–164] use energy to determine levels of mixing, which contrasts to the traditional approach of specifying an a priori diffusivity [165]. Significant questions remain, with further guidance from observations, such as those discussed in the OceanObs'09 White Paper by [11], required to develop and evaluate parameterizations of ocean mixing.

- **Vertical structure of mixing:** Vertical structure of mixing and the scale of its penetration into the ocean interior appear related to characteristics of underlying topography, background flow and stratification, as well as topographic scattering of waves and internal wave-wave interactions [166–168]
- **Partitioning between local and remote dissipation:** Tides generate a mode spectrum of internal waves that is related to the mode spectrum of topography. Low modes are preferentially generated by large-scale topography and have been shown to be stable and long-lived, radiating away from their source, contributing to remote mixing [169]. High modes are generated by small-scale topography, where energy is dissipated locally. In regions of enhanced small scale topographic roughness, such as the Brazil Basin, about 30% (q = 0:3; [170]) of the energy extracted from the barotropic tide goes to high modes [169]; in areas such as the Hawaiian Ridge, low modes dominate, and [171] suggest q = 0:1; whereas in semi enclosed seas such as the Indonesian Archipelago, all the energy remains trapped (q = 1:0) [163]. In those areas with q = 1:0, tidal models suggest a vertical structure of mixing that scales like the squared buoyancy frequency, leading to a parameterization that mimics the internal tidal mixing in the Indonesian Archipelago [172–174].
- Driven by winds or tides? While wind contributes primarily to mixing through generation of internal waves at the ocean surface [175], geostrophic motions may also sustain wave induced mixing in regions like the Southern Ocean [154 and 159]. Surface wave effects also play a role [146].

6.2 Mesoscale and submesoscale

Will fine resolution models, with a well-resolved mesoscale eddy spectrum, significantly alter climate simulations employing coarse resolution and eddy parameterizations? To address this question, it is important to recognize that models require horizontal resolution finer than the Rossby radius (order 50km in mid-latitudes and less than 10km in high latitudes) to capture the mesoscale [176]. At coarser eddy permitting resolutions, it is necessary to retain parameterizations while not overdamping the advectively dominant flow. Traditional Laplacian formulations may not be sufficiently scale selective to meet these objectives [177–181]. As grids are further refined, [182] suggest that large eddy simulation methods will begin to replace Reynolds averaging methods for subgrid-scale parameterizations as the mesoscale becomes partly resolved.

Mesoscale eddies are generally parameterized by variants of the neutral diffusion scheme proposed by [183] and [100], and eddy-induced advection from [101] and [184]. Nonetheless, there remain unresolved issues with mesoscale parameterizations, as well as submesoscales, with the following listing a few.

- **Tracer equation or momentum equation?** There remains discussion regarding the approach of [185], whereby eddy stirring is parameterized as a vertical stress [186–188], in contrast to the more commonly used approach of [101] and [184], where eddy stirring appears as an additional advective tracer transport. Although the two approaches have similar effects after geostrophic adjustment, there may be compelling practical reasons to choose one approach over the other. Other subgrid-scale closures based on Lagrangian-averaging at the subgrid-scale have been proposed and implemented, but remain experimental [189].

- **Form for the diffusivity:** Much work has been given to establishing a scaling theory for a depth independent diffusivity setting the strength of the SGS stirring [190 and 191]. More recently, [192] illustrate the utility of a 3D diffusivity modulated by the squared buoyancy frequency, whereas [193] and [194] propose a 3D diffusivity determined according to the evolving eddy kinetic energy.
- **Matching to the boundary layers:** Questions of how to match interior mesoscale eddy closures to boundary layers continues to generate discussion, with [195] presenting a physically based method; [196] illustrating its utility in ocean climate simulations; and [197] proposing an alternative framework based on solving a boundary value problem.
- **Concerning the submesoscale:** Submesoscale fronts and related instabilities are ubiquitous, and those active in the upper ocean provide a relatively rapid restratification mechanism that should be parameterized in ocean climate simulations [198–201], even those resolving the mesoscale. Other submesoscale frontal effects, including wind-front interactions and appropriate energy cascade dynamics, are currently unaccounted for in ocean climate models [202–205].
- **What about lateral viscous dissipation?** Lateral viscous friction remains the default approach for closing the momentum equation in ocean models. General forms have been advocated based on symmetry and numerical requirements [179, 182, 206–210], with choices significantly impacting simulations at both coarse and fine resolutions [180, 181 and 211]. Large levels of lateral viscous dissipation used by models do not mimic energy dissipation in the real ocean [212]. Yet the status quo (i.e. tuning viscosity to suit the simulation needs) will likely remain the default until a better alternative is realized, or until significantly finer resolution is achieved [182].

6.3 Observations and parameterizations

Many parameterizations are tested against finer resolution simulations that explicitly resolve processes missing at coarse resolutions. Nonetheless, without observational input, parameterizations remain incompletely evaluated, especially for suitability in global climate studies where realistic forcing and geometry can place the flow in a regime distinct from idealized studies. We highlight here a few places where observational studies can be of use for refining and evaluating parameterizations.

- **Overflows:** As reviewed by [150], there are many regions of dense water overflows that provide sources for deep waters. Parameterization of these processes is difficult for many reasons: complexity and uncertainty in the topography; uncertainties in non-dimensional flow parameters; and uncertainty in measured surface fluxes associated with establishing dense water properties. Observational input is critical for resolution of these difficulties.
- **Interior mixing:** Reducing the level of spurious diapycnal mixing in models facilitates collaborative efforts to incorporate mixing theories into simulations, which in turn helps to focus observational efforts to measure mixing and determine its impact on climate [11, 213 and 214].
- **Mesoscale eddies:** Accurate satellite sea level measurements have helped to characterize the surface expression of mesoscale eddies [215–217], and such measures have provided useful input to mesoscale eddy parameterizations [218–225]. We advocate the continuance of satellite missions (e.g. sea level, bottom pressure, sea surface temperature, winds, etc.) in support of developing ocean models. However, satellites are of limited value for characterizing the interior ocean structure, and associated dependencies of eddy effects. Hence, in parallel to satellites, there must remain efforts to provide in situ information on a continuous basis, such as the Argo profiling drifter project [226]. Focused in situ experimental projects are also necessary (like, for example, the Southern Ocean DIMES (Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean),project (http://dimes.ucsd.edu/), or the North Atlantic CLIMODE (CLIVAR (Climate Variability Research Program) Mode Water Dynamic Experiment) project (http://www.climode.org/). Mixed layer maps and climatologies formed from profiles and profiling drifters are valuable for evaluating mixed layer and submesoscale parameterizations [200, 227–230].

7. MODEL DEVELOPMENT AND EVALUATION

The development and use of ocean models require methods to evaluate simulations. For conceptual or process studies, an analytical solution may be available for comparison (e.g. wave processes such as [231 and 232]). More commonly, no analytic solution exists, necessitating comparison to observations, laboratory experiments, or fine scale process simulations. The

CLIVAR website Repository for Evaluating Ocean Simulations (REOS), accessible from http://www.clivar.org/organization/wgomd/wgomd.php is a centralized source for data and a location for the observational community to advertise new products of use for modelers. In this section, we highlight a few examples where observational data has proven essential for evaluating ocean climate simulations. We also note key opportunities for further model-data comparisons.

7.1 Simulations and biases

Fundamental to the task of evaluating a model is the experimental design of simulations. Common experimental designs such as the Atmospheric Model Intercomparison Project (AMIP) [233] render important benchmarks from which to gauge suitability of model classes, and to help identify research gaps. Simulating the global ocean-ice climate with a prescribed atmosphere is more difficult than the complement task: atmospheric fluxes are less well known than sea surface temperature; the representation of important feedbacks is compromised; and there are no unambiguous and suitable methods to set a boundary condition for salinity or fresh water. Ideally, atmospheric reanalysis products would be suitable without modification. But, these products suffer from biases inherent in the atmospheric models, limitations of the assimilation methods, and incomplete data used for assimilation. Furthermore, they are generally not energetically balanced sufficiently for use in long-term ocean climate simulations [234–237].

Consequently, progress has only recently been made for a global ocean-ice model comparison: the Coordinated Ocean-ice Reference Experiments (CORE) [238] using the atmospheric forcing dataset compiled by [235]. Simulations with global ocean-ice models, though possessing problems associated with a non-responsive atmosphere provide a useful complement to simulations with a fully coupled climate model. The principal focus of long-term simulations forced by climatology concerns the model evolution towards a quasi-equilibrium state [238]. For the models forced with historical atmospheric data, direct comparison with observations is available to identify mechanisms of variations on intra-seasonal to decadal timescales [239–241].

The development of atmospheric datasets to force global ocean-ice climate models is a key area where the observational community can greatly support ocean modeling. We advocate continuation of scatterometer missions to constrain momentum fluxes, as well as rainfall measurement missions. Measurements of latent and sensible heating remain a challenge [242] with considerable uncertainty in how to remotely estimate both the air-sea transfer velocities and near-surface air temperatures and relative humidities. An additional challenge is estimation of fluxes through sea ice, where the ocean surface climate is noticeably different from the one in the open ocean. Net fluxes over the Southern Ocean are of order 10 W/m2, which is comparable to uncertainties of individual fluxes. It is possible that constraints on fluxes will come more from assimilating ocean data than from direct estimates.

Ocean components of coupled models are often tuned in ad hoc ways to reduce biases. One common bias arises from weak upwelling on the western side of continents; this bias is even found in ocean simulations such as those in [238]. Field programs and associated process studies, such as VOCALS/VAMOS (VAMOS (Variability of the American Monsoon Systems) Ocean-Cloud-Atmosphere-Land Study) http://www.eol.ucar.edu/projects/vocals/ near the South American coast, are important to enhance understanding and improve measurements to reduce such biases. Furthermore, ocean climate model evaluation has traditionally focused on biases at annual and longer timescales. Hence, the representation of diurnal, intraseasonal, and seasonal variations is relatively poor and requires further observational validation [243–248]. In particular, [244] shows that vertical grid resolution no coarser than one meter and a c are required to represent the diurnal cycle, with [246 and 247] illustrating the importance of a properly resolved diurnal cycle for coupled atmosphere-ocean equatorial dynamics.

7.2 Physics and biology interactions

Reference [249] suggested that, if uncompensated by other processes, variability in the oceanic penetration of shortwave radiation due to phytoplankton could induce heating anomalies of up to 5 □ 10_K/yr over the top 20m. Clearer waters would experience less heating near the surface and more heating at depth. The advent of large-scale models with fine vertical resolution and explicit mixed layer schemes makes it important to correctly represent shortwave radiation absorption [250].

Continued measurements of surface shortwave radiation, and its penetration into the upper ocean, are essential to support simulations of interactions between ocean biology and physics. A challenge is to maintain a stable observational system so changes in the shortwave absorption, associated with changes in ocean biology, can be unambiguously detected.

In ocean-ice models forced with a prescribed atmospheric state, the primary signal of increased shortwave penetration occurs where deeper waters experiencing additional warming upwell to the surface: most notably in the equatorial cold tongue [251–254]. In coupled climate models [255–257], impacts are broader and depend on the region [258]. For example, in the Arctic Ocean, bio-physical feedbacks occur between phytoplankton, ocean dynamics and sea-ice that significantly change the mean state of Earth System models [259]. Continued measurements of surface shortwave radiation, and its penetration into the upper ocean, are essential to support simulations of interactions between ocean biology and physics.

Submesoscale and mesoscale biological effects are expected to be profound due to the potential for large vertical fluxes of nutrients by eddies and fronts [201, 260–262]. The appropriate physical-biological interactions at these scales need to be observed, modeled and parameterized for inclusion in earth system models.

While the observations necessary to constrain ecosystem models are discussed in detail in [263] and the accompanying OceanObs'09 Community White Paper by [10], suggestions have been made that fluxes of biogenic material might act as a potential constraint on watermass transformation [264 and 265]. At a given point, particle fluxes will serve as integrators of the stripping of nutrients from surface water over some "statistical funnel" which may be quite large [266]. However, efforts to use such fluxes to put quantitative constraints on watermass transformation have been limited by both the sparseness of the direct measurements, uncertainty in satellite-based estimates [265], and uncertainties about the depth scale over which sinking particles are consumed and returned to inorganic form. New technologies involving profiling floats that can directly measure both particle concentrations and fluxes offer interesting opportunities in this respect [267].

7.3 Geochemical tracers

Because of uncertainties in both physical processes and fluxes of temperature and salinity, it remains a challenge to constrain net watermass transformation. Chemical tracers present added information of use for this purpose [268]. In particular, ventilation tracers such as chlorofluorocarbons (CFCs) [269] are sensitive to where surface water enters the deep ocean, while tracers like radiocarbon [270] and helium-3 [271] are sensitive to pathways where deep waters return to the surface [272]. Although the usefulness of tracers like CFC-11 is limited since their atmospheric concentration is falling, others (e.g. sulfur hexaflouride) continue to rise. Changes in ocean ventilation can affect ecologically relevant processes like anoxia and productivity. We thus strongly support continued measurement of these tracers.

8. WHAT TO EXPECT BY 2020

The leading edge ocean climate models show significant biases in certain metrics relative to observations, and the models do not always agree on their representation of certain important climate features. The origins of these biases and model differences may be related to shortcomings in grid resolution; improper numerical algorithms; incorrect or missing subgrid scale parameterizations; improper representation of other climate components such as the atmosphere, cryosphere, and biogeochemistry; all of the above, or something else. Understanding and remedying model biases is thus a complex task requiring years of patient and persistent research and development. Ocean observations play a critical role in promoting and supporting these efforts, with this document highlighting specific examples. Our aim in this final section is to consider how observationally better constrained ocean models may impact on answering certain key questions of climate research in the next decade and beyond. By 2020, we believe that new ocean climate models will provide deep insight into the following important issues (amongst many others).

- **AMOC VARIABILITY AND STABILITY:** Atlantic meridional overturning circulation (AMOC) is important for Atlantic climate [273], and it presents an example of how the ocean plays a primary role in long-term climate variations. Models have played an important role in stimulating interest in its behavior (variability and stability) [274–282]. However, data limitations handicap efforts to evaluate simulations. One avenue to increase model reliability is to extend monitoring of key features in the North Atlantic through moorings and Argo floats [226], as well as to promote sound climate models. [283] provide an example where the two efforts complement one another, with models used to assist development of AMOC monitoring such as the RAPID (Research with Adaptive Particle Imaging Detectors) array [284]. By 2020, simulation realism will have advanced, largely through improvements in the representations/parameterizations of key physical processes (e.g. overflows, boundary currents, mesoscale and submesoscale eddies), and reduction of numerical artifacts such as spurious diapycnal mixing. These improvements, coupled to an enhanced observational record possible from long-term (i.e. centennial) support for arrays such as RAPID, will help to identify robust mechanisms for AMOC variability and stability, with such understanding essential to quantify robust limits of predictability and to support predictions with nontrivial skill.

- **PATTERNS OF SEA LEVEL RISE:** The ocean expands as it warms (steric sea level rise). Non-Boussinesq models will enhance the accuracy of simulated patterns of steric sea level rise. Mean sea level may also rise significantly due to ocean-driven dynamic control of ice sheet discharge (e.g. warm ocean waters melt ice shelves, which in turn allows more land ice to flow into the ocean). There are currently no global ocean climate models that simulate the interaction between ocean circulation and continental ice sheets [285]. Yet model enhancements outlined in this document will improve the representation of high latitude heat fluxes, increase resolution near ice-ocean interfaces, and foster the inclusion of a dynamic land-sea boundary.

- **THE SOUTHERN OCEAN:** The Antarctic Circumpolar Current (ACC) has spun-up in response to stronger and more poleward shifted southern westerlies since the 1950s. Changes in the westerlies have been attributed to CO_2 induced warming and to depletion of ozone over Antarctica, both of which have increased the equator-to-pole temperature contrast in the middle atmosphere [286]. These changes are analogous to those as the earth warmed at the end of the ice age [287 and 288]. Theory and models suggest that stronger westerlies and a stronger ACC should induce a stronger AMOC and greater ventilation of the deep Southern Ocean [286]. However, the overturning is expected to weaken due to a stronger hydrological cycle. It is critical that this struggle between stronger westerlies and a stronger hydrological cycle be realistically simulated. Data analysis [289] and eddy permitting simulations [290] indicate that climate models [291] require refined resolution to accurately capture important physical processes (e.g. continental shelf processes, sea ice, mesoscale eddies) active in the Southern Ocean. We anticipate models developed in the next decade will better capture these features, supporting understanding and quantifying uncertainties. Improved observations – through sustained in situ measurements such as Argo [226], continuous satellite observations, and detailed

- bathymetric mapping – will help evaluate such simulations.

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