

# PROBLEMS AND PROSPECTS IN LARGE-SCALE OCEAN CIRCULATION MODELS

S.M. Griffies<sup>(1)</sup>, A.J. Adcroft<sup>(2)</sup>, H. Banks<sup>(3)</sup>, C.W. Böning<sup>(4)</sup>, E.P. Chassignet<sup>(5)</sup>, G. Danabasoglu<sup>(6)</sup>, S. Danilov<sup>(7)</sup>, E. Deleersnijder<sup>(8)</sup>, H. Drange<sup>(9)</sup>, M. England<sup>(10)</sup>, B. Fox-Kemper<sup>(11)</sup>, R. Gerdes<sup>(12)</sup>, A. Gnanadesikan<sup>(13)</sup>, R.J. Greatbatch<sup>(14)</sup>, R.W. Hallberg<sup>(15)</sup>, E. Hanert<sup>(16)</sup>, M.J. Harrison<sup>(17)</sup>, S. Legg<sup>(18)</sup>, C.M. Little<sup>(19)</sup>, G. Madec<sup>(20)</sup>, S.J. Marsland<sup>(21)</sup>, M. Nikurashin<sup>(22)</sup>, A. Pirani<sup>(23)</sup>, H.L. Simmons<sup>(24)</sup>, J. Schröter<sup>(25)</sup>, B.L. Samuels<sup>(26)</sup>, A.-M. Treguier<sup>(27)</sup>, J.R. Toggweiler<sup>(28)</sup>, H. Tsujino<sup>(29)</sup>, G.K. Vallis<sup>(30)</sup>, L. White<sup>(31)</sup>

<sup>(1)</sup> NOAA/Geophysical Fluid Dynamics Laboratory, 201 Forrestal Road, Princeton, NJ 08542, USA. Email: Stephen.Griffies@noaa.gov

<sup>(2)</sup> Princeton University and NOAA/GFDL, 201 Forrestal Road, Princeton, NJ 08542, USA. Email: Alistair.Adcroft@noaa.gov

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

<sup>(4)</sup> Leibniz-Institut für Meereswissenschaften, IFM-GEOMAR, Dienstgebäude Westufer, Düsternbrooker Weg 20, 24105 Kiel, Germany. Email: cboening@ifm-geomar.de

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

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

<sup>(7)</sup> Alfred Wegener Institut für Polar- und Meeresforschung, Bussestr. 24, 27570 Bremerhaven, Germany. Email: sdanilov@awi-bremerhaven.de

<sup>(8)</sup> 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

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

<sup>(10)</sup> 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

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

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

<sup>(13)</sup> NOAA/Geophysical Fluid Dynamics Laboratory, 201 Forrestal Road, Princeton, NJ 08542, USA, Email: Anand.Gnanadesikan@noaa.gov

<sup>(14)</sup> Leibniz-Institut für Meereswissenschaften, IFM-GEOMAR, Dienstgebäude Westufer, Düsternbrooker Weg 20, 24105 Kiel, Germany. Email: rgreatbatch@ifm-geomar.de

<sup>(15)</sup> NOAA/NOAA/Geophysical Fluid Dynamics Laboratory, 201 Forrestal Road, Princeton, NJ 08542, USA, Email: Robert.Hallberg@noaa.gov

<sup>(16)</sup> 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

<sup>(17)</sup> NOAA/NOAA/Geophysical Fluid Dynamics Laboratory, 201 Forrestal Road, Princeton, NJ 08542, USA, Email: Matthew.Harrison@noaa.gov

<sup>(18)</sup> Princeton University and NOAA/GFDL, 201 Forrestal Road, Princeton, NJ 08542, USA, Email: Sonya.Legg@noaa.gov

<sup>(19)</sup> Princeton University Geosciences Program, 201 Forrestal Road, Princeton, NJ 08542, USA, Email: cmlittle@Princeton.edu

<sup>(20)</sup> Laboratoire d'Océanographie et du Climat, CNRS-UPMC-IRD, Paris, France, and National Oceanography Centre, Southampton, University of Southampton Waterfront Campus, European Way, Southampton SO14 3ZH, United Kingdom. Email: Gurvan.Madec@lodyc.jussieu.fr

<sup>(21)</sup> The Centre for Australian Weather and Climate Research, Private Bag 1, Aspendale, VIC 3195, Australia. Email: Simon.Marsland@csiro.au

<sup>(22)</sup> Princeton University and NOAA/GFDL, 201 Forrestal Road, Princeton, NJ 08542, USA, Email: Maxim.Nikurashin@noaa.gov

<sup>(23)</sup> International CLIVAR Project Office, Southampton, UK, and Princeton University AOS Program, 300 Forrestal Road, Sayre Hall, Princeton, NJ 08544, Email: anna.pirani@noc.soton.ac.uk

<sup>(24)</sup> International Arctic Research Center, 930 Koyukuk Drive, P.O. Box 757340, Fairbanks, Alaska 99775-7340, USA. Email: hsimmons@iarc.uaf.edu

<sup>(25)</sup> Alfred Wegener Institut für Polar- und Meeresforschung, Bussestr. 24, 27570 Bremerhaven, Germany. Email: Jens.Schroeter@awi.de

<sup>(26)</sup> NOAA/Geophysical Fluid Dynamics Laboratory, 201 Forrestal Road, Princeton, NJ 08542, USA, Email: Bonnie.Samuels@noaa.gov

<sup>(27)</sup> Laboratoire de Physique des Océans, UMR 6523 CNRS-IFREMER-IRD-UBO, IUEM, Ifremer, BP 70, 29280 Plouzane, France. Email: Anne.Marie.Treguier@ifremer.fr

<sup>(28)</sup> NOAA/Geophysical Fluid Dynamics Laboratory, 201 Forrestal Road, Princeton, NJ 08542, USA, Email: Robbie.Toggweiler@noaa.gov

<sup>(29)</sup> Japan Meteorological Agency/Meteorological Research Institute, Nagamine 1-1, Tsukuba, Ibaraki 305-0052, Japan. Email: htsujino@mri-jma.go.jp

<sup>(30)</sup> Princeton University and NOAA/GFDL, 201 Forrestal Road, Princeton, NJ 08542, USA, Email: Geoffrey.Vallis@noaa.gov

<sup>(31)</sup> 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 Ocean Obs 2009 workshop 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 Ocean Obs 2009 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 recommenda-

tions 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 1500

m/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 sub-grid 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 (Section 5), and the method of averaging (Section 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, 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, 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, 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, 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, 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 (Section 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 (Section 5.2), yet optimal strategies for unstructured mesh models remain under investigation.
- **Analysis:** New tools are required to analyze unstructured mesh simulations [79, 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 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 [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, 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, 85].
- Mesoscale eddy models can exhibit numerical diapycnal diffusion far larger than is observed [86, 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, 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 ( $\sigma_0$ ) 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,  $\sigma_{2000}$  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,  $\sigma_{2000}$  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, 113]. These more gen-

eral 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  $\sigma_{2000}$  surfaces are impervious to adiabatic advection. But it is unclear whether approximating neutral surfaces by  $\sigma_{2000}$  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 [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 [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  $10^8$ ; i.e., dianeutral diffusivity is roughly  $10^{-5} \text{m}^2/\text{sec}$ . Furthermore, theory [124] and observations [125] suggest even smaller values ( $10^{-6} \text{m}^2/\text{sec}$ ; 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, 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, 148]. [149, 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, 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 Ocean Obs 2009 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, 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 subgridscale 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 subgridscale closures based on Lagrangian-averaging at the subgridscale 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, 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, 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, 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]. Focussed *in situ* experimental projects are also necessary (like, for example, the Southern Ocean DIMES project (<http://dimes.ucsd.edu>), or the North Atlantic CLIMODE 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, 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 than open ocean. Net fluxes over the Southern Ocean are of



order  $10 \text{ W/m}^2$ , 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 (<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] show that vertical grid resolution no coarser than one meter and a coupling period no longer than two hours are required to represent the diurnal cycle, with [246, 247] illustrating the importance of a properly resolved diurnal cycle for coupled atmosphere-ocean equatorial dynamics.

## 7.2 Physics and biology interactions

[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  $5 - 10^\circ \text{K/yr}$  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 changes 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 Ocean Obs 2009 Community White Paper by [10], suggestions have been made that fluxes of biogenic material might act as a potential constraint on watermass transformation [264, 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 both by 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 hexafluoride) 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 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, 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.

#### Acknowledgements

Some of the material in this paper arose from the workshops **Numerical Methods in Ocean Models**, held in Bergen, Norway in August 2007, and **Ocean Mesoscale Eddies: Representations, Parameterizations, and Observations**, held in Exeter, UK in May 2009. Both workshops were organized by CLIVAR’s Working Group on Ocean Model Development (WGOMD). Further information, including workshop presentations, can be found at the WGOMD website:

<http://www.clivar.org/organization/wgomd/wgomd.php>

Eric Deleersnijder is a Research associate with the Belgian National Fund for Scientific Research (F.R.S.-FNRS). Anna Pirani is sponsored by a Subaward with the University Corporation for Atmospheric Research (UCAR) under the sponsorship of the National Science Foundation (NSF). We thank Kirk Bryan, Patrick Heimbach, Torge Martin and Tony Rosati for comments on early drafts of this paper. This paper is dedicated to the memory of Peter Killworth.

## References

1. Balmaseda, M. *et al.* Initialization for seasonal and decadal forecasts. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
2. Heimbach, P. *et al.* Observational requirements for global-scale ocean climate analysis: Lessons from ocean state estimation. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
3. Hurrell, J. *et al.* Decadal climate prediction: Opportunities and challenges. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
4. Latif, M. *et al.* Dynamics of decadal climate variability and implications for its prediction. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
5. Lee, T. *et al.* Ocean state estimation for climate research. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
6. Le Traon, P., Bell, M., Dombrowsky, E., Schiller, A. & Wilmer-Becker, K. GODAE OceanView: from an experiment towards a long-term ocean analysis and forecasting international program. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
7. Rienecker, M. *et al.* Synthesis and assimilation systems: Essential adjuncts to the global ocean observing system. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
8. Stammer, D. *et al.* Ocean variability evaluated from an ensemble of ocean syntheses. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
9. Xue, Y. *et al.* Ocean state estimation for global ocean monitoring: ENSO and beyond ENSO. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference (Vol. 2): Sustained Ocean Observations and Information for Society*, vol. 2 (ESA Publication WPP-306, 2010).
10. LeQuere, C. *et al.* Observational needs of dynamic green ocean models. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
11. MacKinnon, J. *et al.* Using global arrays to investigate internal-waves and mixing. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
12. Arakawa, A. & Lamb, V. (1981). A potential enstrophy and energy conserving scheme for the shallow water equations. *Monthly Weather Review* **109**, 18–36.
13. Griffies, S. M. *et al.* (2000). Developments in ocean climate modelling. *Ocean Modelling* **2**, 123–192.
14. Griffies, S. M. & Adcroft, A. J. Formulating the equations for ocean models. In Hecht, M. & Hasumi, H. (eds.) *Eddy resolving ocean models*, Geophysical Monograph 177, 281–317 (American Geophysical Union, 2008).
15. Nadiga, B. T., Taylor, M. & Lorenz, J. (2006). Ocean modelling for climate studies: Eliminating short time scales in long-term, high-resolution studies of ocean circulation. *Mathematical and Computer Modelling* **44**, 870–886.
16. Marshall, J., Hill, C., Perelman, L. & Adcroft, A. (1997). Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling. *Journal of Geophysical Research* **102**, 5733–5752.
17. Mahadevan, A. (2006). Modeling vertical motion at ocean fronts: Are nonhydrostatic effects relevant at submesoscales? *Ocean Modelling* **14**, 222–240.

18. Sprague, M., Julien, K., Knobloch, E. & Werne, J. (2006). Numerical simulation of an asymptotically reduced system for rotationally constrained convection. *Journal of Fluid Mechanics* **551**, 141–174.
19. Greatbatch, R. J. (1994). A note on the representation of steric sea level in models that conserve volume rather than mass. *Journal of Geophysical Research* **99**, 12767–12771.
20. Huang, R. X., Jin, X. & Zhang, X. (2001). An oceanic general circulation model in pressure coordinates. *Advances in Atmospheric Physics* **18**, 1–22.
21. DeSzoeke, R. A. & Samelson, R. M. (2002). The duality between the Boussinesq and non-Boussinesq hydrostatic equations of motion. *Journal of Physical Oceanography* **32**, 2194–2203.
22. Losch, M., Adcroft, A. & Campin, J.-M. (2004). How sensitive are coarse general circulation models to fundamental approximations in the equations of motion? *Journal of Physical Oceanography* **34**, 306–319.
23. Marshall, J., Adcroft, A., Campin, J.-M., Hill, C. & White, A. (2004). Atmosphere-ocean modeling exploiting fluid isomorphisms. *Monthly Weather Review* **132**, 2882–2894.
24. Salmon, R. (2004). Poisson-bracket approach to the construction of energy- and potential-estrophy-conserving algorithms for the shallow-water equations. *Journal of Physical Oceanography* **61**, 2016–2036.
25. Salmon, R. (2007). A general method for conserving energy and potential enstrophy in shallow-water models. *Journal of the Atmospheric Sciences* **64**, 515–531.
26. Griffies, S. M., Pacanowski, R., Schmidt, M. & Balaji, V. (2001). Tracer conservation with an explicit free surface method for  $z$ -coordinate ocean models. *Monthly Weather Review* **129**, 1081–1098.
27. Campin, J.-M., Adcroft, A., Hill, C. & Marshall, J. (2004). Conservation of properties in a free-surface model. *Ocean Modelling* **6**, 221–244.
28. Griffies, S. M. *Fundamentals of Ocean Climate Models* (Princeton University Press, Princeton, USA, 2004). 518+xxxiv pages.
29. Shchepetkin, A. & McWilliams, J. (2005). The regional oceanic modeling system (roms): a split-explicit, free-surface, topography-following-coordinate oceanic model. *Ocean Modelling* **9**, 347–404.
30. White, L., Legat, V. & Deleersnijder, E. (2008). Tracer conservation for three-dimensional, finite element, free-surface, ocean modeling on moving prismatic meshes. *Monthly Weather Review* **136**, 420–442.
31. Leclair, M. & Madec, G. (2009). A conservative leapfrog time-stepping method. *Ocean Modelling* **30**, 88–94.
32. LeVeque, R. J. *Finite Volume Methods for Hyperbolic Problems*. Cambridge Texts in Applied Mathematics (Cambridge Press, Cambridge, England, 2002). 578 pp.
33. Machenhauer, B., Kaas, E. & Lauritzen, P. Finite-volume methods in meteorology. In Temam, R. & Tribbia, J. (eds.) *Computational Methods for the Atmosphere and the Oceans*, 761 (Elsevier, Amsterdam, 2009).
34. Adcroft, A., Hill, C. & Marshall, J. (1997). Representation of topography by shaved cells in a height coordinate ocean model. *Monthly Weather Review* **125**, 2293–2315.
35. Pacanowski, R. C. & Gnanadesikan, A. (1998). Transient response in a  $z$ -level ocean model that resolves topography with partial-cells. *Monthly Weather Review* **126**, 3248–3270.
36. Adcroft, A., Hallberg, R. & Harrison, M. (2008). A finite volume discretization of the pressure gradient force using analytic integration. *Ocean Modelling* **22**, 106–113.
37. Griffies, S. M. *Elements of MOM4p1* (NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, USA, 2009). 444 pp.
38. Adcroft, A., Campin, J., Hill, C. & Marshall, J. (2004). Implementation of an atmosphere-ocean general circulation model on the expanded spherical cube. *Monthly Weather Review* **132**, 2845–2863.
39. Sadourny, R., Arakawa, A. & Mintz, Y. (1968). Integration of the non-divergent barotropic vorticity equation with an icosahedral-hexagonal grid for the sphere. *Monthly Weather Review* **96**, 351–356.
40. Randall, D., Ringler, T., Heikes, R., Jones, P. & Baumgardner, J. (2002). Climate modeling with spherical geodesic grids. *Computing in Science and Engineering* **4**, 32–41.
41. Bonaventura, L. *et al.* (2004). The icon shallow water model: Scientific documentation and benchmark tests. Available from <http://www.icon.enes.org/>.

42. Ringler, T., Ju, L. & Gunzburger, M. (2008). A multiresolution method for climate system modeling: application of spherical centroidal voronoi tessellations. *Ocean Dynamics* **58**, 475–498.
43. Comblen, R., Legrand, S., Deleersnijder, E. & Legat, V. (2009). A finite element method for solving the shallow water equations on the sphere. *Ocean Modelling* **28**, 13–23.
44. Stuhne, G. & Peltier, W. (2006). *Journal of Computational Physics* **213**, 704–729.
45. Casulli, V. & Walters, R. A. (2000). An unstructured grid, three-dimensional model based on the shallow-water equations. *International Journal of Numerical Methods in Fluids* **32**, 331–346.
46. Chen, C., Liu, H. & Beardsley, R. (2003). An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: applications to coastal ocean and estuaries. *Journal of Atmospheric and Oceanic Technology* **20**, 159–186.
47. Murray, R. J. (1996). Explicit generation of orthogonal grids for ocean models. *Journal of Computational Physics* **126**, 251–273.
48. Debreu, L. & Blayo, E. (2008). Two-way embedding algorithms: a review. *Ocean Dynamics* **58**, 415–428.
49. Slingo, J. *et al.* (2009). Developing the next-generation climate system models: challenges and achievements. *Philosophical Transactions of the Royal Society A* **367**, 815–831.
50. Schwanenberg, D., Kiem, R. & Kongeter, J. A discontinuous Galerkin method for the shallow-water equations with source terms. In Cockburn, B., Karniadaki, G. E. & Chu, C.-W. (eds.) *Discontinuous Galerkin Methods: Theory, Computations and Applications*, vol. 11 of *Lecture Notes in Computational Science and Engineering*, 419–424 (Springer, Berlin, 2000).
51. Aizinger, V. & Dawson, C. (2002). A discontinuous Galerkin method for two-dimensional flow and transport in shallow water. *Advances in Water Resources* **25**, 67–84.
52. Nair, R. D., Thomas, S. J. & Loft, R. D. (2005). A discontinuous Galerkin global shallow water model. *Monthly Weather Review* **133**, 876–888.
53. Levin, J. C., Iskandarani, M. & Haidvogel, D. B. (2006). To continue or discontinue: Comparison of continuous and discontinuous Galerkin formulations in a spectral element ocean model. *Ocean Modelling* **15**, 56–70.
54. Bernard, P.-E., Chevaugnon, N., Legat, V., Deleersnijder, E. & Remacle, J.-F. (2007). High-order  $h$ -adaptive discontinuous Galerkin methods for ocean modeling. *Ocean Dynamics* **57**, 109–121.
55. Lynch, D. R. & Werner, F. E. (1987). Three-dimensional hydrodynamics on finite elements. Part I: linearized harmonic model. *International Journal of Numerical Methods in Fluids* **7**, 871–909.
56. Walters, R. A. & Werner, F. E. (1989). A comparison of two finite element models of tidal hydrodynamics using the North Sea data set. *Advances in Water Resources* **12**, 184–193.
57. Fringer, O. B., Gerritsen, M. & Street, R. L. (2006). An unstructured-grid, finite-volume, non hydrostatic, parallel coastal ocean simulator. *Ocean Modelling* **14**, 139–173.
58. Westerink, J. J. *et al.* (2008). A basin- to channel-scale unstructured grid hurricane storm surge model applied to southern Louisiana. *Monthly Weather Review* **136**, 833–864.
59. Myers, P. G. & Weaver, A. J. (1995). A diagnostic barotropic finite-element ocean circulation model. *Journal of Atmospheric and Oceanic Technology* **12**, 511–526.
60. Greenberg, D. A., Werner, F. E. & Lynch, D. R. (1998). A diagnostic finite element ocean circulation model in spherical-polar coordinates. *Journal of Atmospheric and Oceanic Technology* **15**, 942–958.
61. Timmermann, R. *et al.* (2009). Ocean circulation and sea ice distribution in a finite element global sea ice-ocean model. *Ocean Modelling* **27**, 114–129.
62. Le Roux, D. Y., Staniforth, A. & Lin, C. A. (1998). Finite elements for shallow-water equation ocean models. *Monthly Weather Review* **126**, 1931–1951.
63. Hanert, E., Legat, V. & Deleersnijder, E. (2003). A comparison of three finite elements to solve the linear shallow water equations. *Ocean Modelling* **5**, 17–35.
64. Le Roux, D. Y., Sène, A., Rostand, V. & Hanert, E. (2005). On some spurious mode issues in shallow-water models using a linear algebra approach. *Ocean Modelling* **10**, 83–94.
65. Piggott, M. D. *et al.* (2008). A new computational framework for multi-scale ocean modelling based on adapting unstructured meshes. *International Journal of Numerical Methods in Fluids* **56**, 1003–1015.
66. Hanert, E., Walters, R. A., Roux, D. Y. L. & Pietrzak, J. D. (2009). A tale of two elements:  $P_1^{NC} - P_1$  and  $RT_0$ . *Ocean Modelling* **28**, 24–33.

67. Comblen, R., Lambrechts, J., Remacle, J.-F. & Legat, V. (2009). Practical evaluation of five partly-discontinuous finite element pairs for the non-conservative shallow water equations. *International Journal of Numerical Methods in Fluids* Accepted.
68. Le Roux, D. Y., Lin, C. A. & Staniforth, A. (2000). A semi-implicit semi-Lagrangian finite element shallow-water ocean model. *Monthly Weather Review* **128**, 1384–1401.
69. Hanert, E., Le Roux, D. Y., Legat, V. & Deleersnijder, E. (2004). Advection schemes for unstructured grid ocean modelling. *Ocean Modelling* **7**, 39–58.
70. Hanert, E., Le Roux, D. Y., Legat, V. & Deleersnijder, E. (2005). An efficient Eulerian finite element method for the shallow water equations. *Ocean Modelling* **10**, 115–136.
71. Iskandarani, M., Levin, J. C., Choi, B.-J. & Haidvogel, D. B. (2005). Comparison of advection schemes for high-order h-p finite element and finite volume methods. *Ocean Modelling* **10**, 51–67.
72. Kubatko, E. J., Westerink, J. J. & Dawson, C. (2006). *hp* Discontinuous Galerkin methods for advection dominated problems in shallow water flow. *Comput. Meth. Appl. Mech. Eng.* **196**, 437–451.
73. Le Roux, D. Y. (2005). Dispersion relation analysis of the  $P_1^{NC} - P_1$  finite-element pair in shallow-water models. *SIAM J. Sci. Comput.* **27**, 394–414.
74. White, L., Legat, V., Deleersnijder, E. & Le Roux, D. (2006). A one-dimensional benchmark for the propagation of Poincaré waves. *Ocean Modelling* **15**, 101–123.
75. Le Roux, D. Y., Rostand, V. & Pouliot, B. (2007). Analysis of numerically induced oscillations in 2D finite-element shallow-water models. Part I: inertia-gravity waves. *SIAM J. Sci. Comput.* **29**, 331–360.
76. Bernard, P.-E., Deleersnijder, E., Legat, V. & Remacle, J.-F. (2008). Dispersion analysis of discontinuous Galerkin schemes applied to Poincaré, Kelvin and Rossby waves. *J. Sci. Comput.* **34**, 26–47.
77. Bernard, P.-E., Remacle, J.-F. & Legat, V. (2009). Modal analysis on unstructured meshes of the dispersion properties of the  $P_1^{NC} - P_1$  pair. *Ocean Modelling* **28**, 2–11.
78. Le Roux, D. Y., Hanert, E., Rostand, V. & Pouliot, B. (2009). Impact of mass lumping on gravity and Rossby waves in 2D finite-element shallow-water models. *International Journal of Numerical Methods in Fluids* **59**, 767–790.
79. Cotter, C. & Gorman, G. (2008). Diagnostic tools for 3d unstructured oceanographic data. *Ocean Modelling* **20**, 170–182.
80. Sidorenko, D., Danilov, S., Wang, Q., Huerta-Casas, A. & Schröter, J. (2009). On computing transports in finite-element models. *Ocean Modelling* **28**, 60–65.
81. Danilov, S., Wang, Q., Losch, M., Sidorenko, D. & Schröter, J. (2008). Modeling ocean circulation on unstructured meshes: comparison of two horizontal discretizations. *Ocean Dynamics* **58**, 365–374.
82. Meehl, G. *et al.* (2007). The wcrp cmip3 multi-model dataset: A new era in climate change research. *Bulletin of the American Meteorological Society* **88**, 1383–1394.
83. Barnier, B. *et al.* (2006). Impact of partial steps and momentum advection schemes in a global ocean circulation model at eddy permitting resolution. *Ocean Dynamics* **56**, 543–567.
84. Penduff, T. *et al.* (2007). Influence of numerical schemes on current-topography interactions in  $1/4^{\text{deg}}$  global ocean simulations. *Ocean Science* **3**, 509–524.
85. Le Sommer, J., Penduff, T., Theetten, S., Madec, G. & Barnier, B. (2009). How momentum advection schemes influence current-topography interactions at eddy permitting resolution. *Ocean Modelling* **29**, 1–14.
86. Griffies, S. M., Pacanowski, R. C. & Hallberg, R. W. (2000). Spurious diapycnal mixing associated with advection in a  $z$ -coordinate ocean model. *Monthly Weather Review* **128**, 538–564.
87. Lee, M.-M., Coward, A. C. & Nurser, A. G. (2002). Spurious diapycnal mixing of deep waters in an eddy-permitting global ocean model. *Journal of Physical Oceanography* **32**, 1522–1535.
88. Roberts, M. J. & Wood, R. (1997). Topographic sensitivity studies with a Bryan-Cox-type ocean model. *Journal of Physical Oceanography* **27**, 823–836.
89. Winton, M., Hallberg, R. & Gnanadesikan, A. (1998). Simulation of density-driven frictional downslope flow in  $z$ -coordinate ocean models. *Journal of Physical Oceanography* **28**, 2163–2174.
90. Dietrich, D., Marietta, M. & Roache, P. (1987). An ocean modeling system with turbulent boundary layers and topography: Part 1. numerical studies of small island wakes in the ocean. *International Journal of Numerical Methods in Fluids* **7**, 833–855.

91. Beckmann, A. & Döscher, R. (1997). A method for improved representation of dense water spreading over topography in geopotential-coordinate models. *Journal of Physical Oceanography* **27**, 581–591.
92. Beckmann, A. The representation of bottom boundary layer processes in numerical ocean circulation models. In Chassignet, E. P. & Verron, J. (eds.) *Ocean Modeling and Parameterization*, vol. 516 of *NATO ASI Mathematical and Physical Sciences Series*, 135–154 (Kluwer, 1998).
93. Price, J. & Yang, J. Marginal sea overflows for climate simulations. In Chassignet, E. P. & Verron, J. (eds.) *Ocean Modeling and Parameterization*, vol. 516 of *NATO ASI Mathematical and Physical Sciences Series*, 155–170 (Kluwer, 1998).
94. Killworth, P. D. & Edwards, N. (1999). A turbulent bottom boundary layer code for use in numerical ocean models. *Journal of Physical Oceanography* **29**, 1221–1238.
95. Campin, J.-M. & Goosse, H. (1999). Parameterization of density-driven downsloping flow for a coarse-resolution ocean model in  $z$ -coordinate. *Tellus* **51A**, 412–430.
96. Nakano, H. & Suginohara, N. (2002). Effects of bottom boundary layer parameterization on reproducing deep and bottom waters in a world ocean model. *Journal of Physical Oceanography* **32**, 1209–1227.
97. Wu, W., Danabasoglu, G. & Large, W. (2007). On the effects of parameterized mediterranean overflow on North Atlantic ocean circulation and climate. *Ocean Modelling* **19**, 31–52.
98. Legg, S., Hallberg, R. & Girton, J. (2006). Comparison of entrainment in overflows simulated by  $z$ -coordinate, isopycnal and non-hydrostatic models. *Ocean Modelling* **11**, 69–97.
99. Marchesiello, J. M. P., Debreu, L. & Couvelard, X. (2009). Spurious diapycnal mixing in terrain-following coordinate models: The problem and a solution. *Ocean Modelling* **26**, 156–169.
100. Redi, M. H. (1982). Oceanic isopycnal mixing by coordinate rotation. *Journal of Physical Oceanography* **12**, 1154–1158.
101. Gent, P. R. & McWilliams, J. C. (1990). Isopycnal mixing in ocean circulation models. *Journal of Physical Oceanography* **20**, 150–155.
102. Haney, R. L. (1991). On the pressure gradient force over steep topography in sigma-coordinate ocean models. *Journal of Physical Oceanography* **21**, 610–619.
103. Deleersnijder, E. & Beckers, J.-M. (1992). On the use of the  $\sigma$ -coordinate system in regions of large bathymetric variations. *Journal of Marine Systems* **3**, 381–390.
104. Beckmann, A. & Haidvogel, D. (1993). Numerical simulation of flow around a tall isolated seamount. part i: Problem formulation and model accuracy. *Journal of Physical Oceanography* **23**, 1736–1753.
105. Shchepetkin, A. & McWilliams, J. (2002). A method for computing horizontal pressure-gradient force in an ocean model with a non-aligned vertical coordinate. *Journal of Geophysical Research* **108**, 35.1–35.34.
106. Hallberg, R. W. The suitability of large-scale ocean models for adapting parameterizations of boundary mixing and a description of a refined bulk mixed layer model. In Müller, P. & Garrett, C. (eds.) *Near-Boundary Processes and Their Parameterization*, Proceedings of the 13th 'Aha Huliko'a Hawaiian Winter Workshop, 187–203 (University of Hawaii at Manoa, 2003).
107. McDougall, T. & Jackett, D. (2005). An assessment of orthobaric density in the global ocean. *Journal of Physical Oceanography* **35**, 2054–2075.
108. Sun, S. *et al.* (1999). Inclusion of thermobaricity in isopycnic-coordinate ocean models. *Journal of Physical Oceanography* **29**, 2719–2729.
109. Hallberg, R. (2005). A thermobaric instability in Lagrangian vertical coordinate ocean models. *Ocean Modelling* **8**, 227–300.
110. Bleck, R. On the use of hybrid vertical coordinates in ocean circulation modeling. In Chassignet, E. P. & Verron, J. (eds.) *Ocean Weather Forecasting: an Integrated View of Oceanography*, vol. 577, 109–126 (Springer, 2005).
111. Hallberg, R. W. (2000). Time integration of diapycnal diffusion and Richardson number-dependent mixing in isopycnal coordinate ocean models. *Monthly Weather Review* **128**, 1402–1419.
112. Iudicone, D., Madec, G. & McDougall, T. (2008). Water-mass transformations in a neutral density framework and the key role of light penetration. *Journal of Physical Oceanography* **38**, 1357–1376.
113. Klocker, A. & McDougall, T. (2009). Quantifying the consequences of the ill-defined nature of neutral surfaces. *Journal of Physical Oceanography* **in press**.
114. White, L. & Adcroft, A. (2008). A high-order finite volume remapping scheme for nonuniform grids: The piecewise quartic method (PQM). *Journal of Computational Physics* **227**, 7394–7422.

115. Griffies, S. M. *et al.* (1998). Isoneutral diffusion in a  $z$ -coordinate ocean model. *Journal of Physical Oceanography* **28**, 805–830.
116. Hallberg, R. & Adcroft, A. (2009). Reconciling estimates of the free surface height in lagrangian vertical coordinate ocean models with mode-split time stepping. *Ocean Modelling* **29**, 15–26.
117. Bleck, R. (2002). An oceanic general circulation model framed in hybrid isopycnic-cartesian coordinates. *Ocean Modelling* **4**, 55–88.
118. Chassignet, E., Smith, L., Halliwell, G. & Bleck, R. (2003). North Atlantic simulation with the HYbrid Coordinate Ocean model (HYCOM): Impact of the vertical coordinate choice, reference density, and thermobaricity. *Journal of Physical Oceanography* **33**, 2504–2526.
119. Halliwell, G. R. (2004). Evaluation of vertical coordinate and vertical mixing algorithms in the HYbrid Coordinate Ocean Model (HYCOM). *Ocean Modelling* **7**, 285–322.
120. Donea, J., Huerta, A., Ponthot, J.-P. & Rodríguez-Ferran, A. Arbitrary Lagrangian-Eulerian methods. In Stein, E., de Borst, R. & Hughes, T. J. R. (eds.) *Encyclopedia of Computational Mechanics*, chap. 14 (John Wiley and Sons, 2004).
121. Bleck, R. & Smith, L. (1990). A wind-driven isopycnic coordinate model of the North and Equatorial Atlantic Ocean. 1: Model development and supporting experiments. *Journal of Geophysical Research* **95**, 3273–3285.
122. McDougall, T. J. (1987). Neutral surfaces. *Journal of Physical Oceanography* **17**, 1950–1967.
123. Ledwell, J. R., Watson, A. J. & Law, C. S. (1993). Evidence for slow mixing across the pycnocline from an open-ocean tracer-release experiment. *Nature* **364**, 701–703.
124. Henyey, F., Wright, J. & Flatte, S. (1986). Energy and action flow through the internal wave field: an eikonal approach. *Journal of Geophysical Research* **91**, 8487–8496.
125. Gregg, M., Sanford, T. & Winkel, D. (2003). Reduced mixing from the breaking of internal waves in equatorial waters. *Nature* **422**, 513–515.
126. Harrison, M. & Hallberg, R. (2008). Pacific subtropical cell response to reduced equatorial dissipation. *Journal of Physical Oceanography* **38**, 1894–1912.
127. Niiler, P. & Kraus, E. One-dimensional models of the upper ocean. In Kraus, E. (ed.) *Modelling and prediction of the upper layers of the ocean*, Proceedings of a NATO advanced study institute, 143–172 (Pergamon Press, 1977).
128. Pacanowski, R. C. & Philander, G. (1981). Parameterization of vertical mixing in numerical models of the tropical ocean. *Journal of Physical Oceanography* **11**, 1442–1451.
129. Mellor, G. L. & Yamada, T. (1982). Development of a turbulent closure model for geophysical fluid problems. *Reviews of Geophysics* **20**, 851–875.
130. Gaspar, P., Gregoris, Y. & Lefevre, J. (1990). A simple eddy kinetic energy model for simulations of the oceanic vertical mixing: Tests at station Papa and long-term upper ocean study site. *Journal of Geophysical Research* **95**, 16179–16193.
131. Large, W. G., McWilliams, J. C. & Doney, S. C. (1994). Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Reviews of Geophysics* **32**, 363–403.
132. Chen, D., Rothstein, L. & Busalacchi, A. (1994). A hybrid vertical mixing scheme and its application to tropical ocean models. *Journal of Physical Oceanography* **24**, 2156–2179.
133. Noh, Y. & Kim, H.-J. (1999). Simulations of temperature and turbulence structure of the oceanic boundary layer with the improved near-surface process. *Journal of Geophysical Research* **104**, 15,621–15,634.
134. Canuto, V., Howard, A., Cheng, Y. & Dubovikov, M. (2002). Ocean turbulence. part ii: vertical diffusivities of momentum, heat, salt, mass, and passive scalars. *Journal of Physical Oceanography* **32**, 240–264.
135. Umlauf, L. & Burchard, H. (2005). Second-order turbulence closure models for geophysical boundary layers. a review of recent work. *Continental Shelf Research* **25**, 795–827.
136. Noh, Y., Kang, Y.-J., Matsuura, T. & Iizuka, S. (2005). Effect of the prandtl number in the parameterization of vertical mixing in an ogcm of the tropical pacific. *Journal of Geophysical Research* **32** L23609, doi:10.1029/2005GL024540.
137. Jackson, L., Hallberg, R. & Legg, S. (2008). A parameterization of shear-driven turbulence for ocean climate models. *Journal of Physical Oceanography* **38**, 1033–1053.
138. Moon, I.-J., Ginis, I. & Hara, T. (2004). Effect of surface waves on air-sea momentum exchange. Part II: Behavior of drag coefficient under tropical cyclones. *JAS* **61**, 2334–2348.



139. Kantha, L. & Clayson, C. (2004). On the effect of surface gravity waves on mixing in the oceanic mixed layer. *Ocean Modelling* **6**, 101–124.
140. Sullivan, P. P., McWilliams, J. C. & Melville, W. K. (2007). Surface gravity wave effects in the oceanic boundary layer: large-eddy simulation with vortex force and stochastic breakers. *Journal of Fluid Mechanics* **593**, 405–452.
141. Gargett, A. E. & Wells, J. R. (2007). Langmuir turbulence in shallow water. part 1. observations. *Journal of Fluid Mechanics* **576**, 27–61.
142. Tejada-Martinez, A. E. & Grosch, C. E. (2007). Langmuir turbulence in shallow water. part 2. large-eddy simulation. *Journal of Fluid Mechanics* **576**, 63–108.
143. D'Asaro, E. A. & Lien, R.-C. (2007). Measurement of scalar variance dissipation from Lagrangian floats. *Journal of Atmospheric and Oceanic Technology* **24**, 1066–1077.
144. Harcourt, R. R. & D'Asaro, E. A. (2008). Large-eddy simulation of langmuir turbulence in pure wind seas. *Journal of Physical Oceanography* **38**, 1542–1562.
145. Polton, J. A. & Belcher, S. E. (2007). Langmuir turbulence and deeply penetrating jets in an unstratified mixed layer. *Journal of Geophysical Research-Oceans* **112**.
146. Polton, J. A., Smith, J. A., MacKinnon, J. A. & Tejada-Martinez, A. E. (2008). Rapid generation of high-frequency internal waves beneath a wind and wave forced oceanic surface mixed layer. *Geophysical Research Letters* **35**.
147. Papadakis, M., Chassignet, E. & Hallberg, R. (2003). Numerical simulations of the Mediterranean Sea outflow: Impact of the entrainment parameterization in an isopycnic coordinate model. *Ocean Modelling* **5**, 325–356.
148. Xu, X., Chassignet, E., Price, J., Özgökmen, T. M. & Peters, H. (2007). A regional modeling study of the entraining mediterranean outflow. *Journal of Geophysical Research* **112**, C12005, doi:10.1029/2007JC004145.
149. Legg, S., Jackson, L. & Hallberg, R. Eddy-resolving modeling of overflows. In Hecht, M. & Hasumi, H. (eds.) *Eddy resolving ocean models*, Geophysical Monograph 177, 63–82 (American Geophysical Union, 2008).
150. Legg, S. *et al.* (2009). Improving oceanic overflow representation in climate models: The Gravity Current Entrainment Climate Process Team. *Bulletin of the American Meteorological Society* **90**, 657–670.
151. Kunze, E., Firing, E., Hummon, J., Chereskin, T. & Thurnherr, A. M. (2006). Global abyssal mixing inferred from lowered adcp shear and ctd strain profiles. *Journal of Physical Oceanography* **36**, 1553–1576.
152. Jochum, M. (2009). Impact of latitudinal variations in vertical diffusivity on climate simulations. *Journal of Geophysical Research* **114** C01010, doi:10.1029/2008JC005030.
153. Polzin, K., Toole, J., Ledwell, J. & Schmitt, R. (1997). Spatial variability of turbulent mixing in the abyssal ocean. *Science* **276**, 93–96.
154. Munk, W. & Wunsch, C. (1998). Abyssal recipes ii: Energetics of tidal and wind mixing. *Deep-Sea Research* **45**, 1977–2010.
155. Ledwell, J. *et al.* (2000). Evidence for enhanced mixing over rough topography. *Nature* **403**, 179–182.
156. St. Laurent, L., Toole, J. & Schmitt, R. (2001). Buoyancy forcing by turbulence above rough topography in the abyssal brazil basin. *Journal of Physical Oceanography* **31**, 3476–3495.
157. Polzin, K. L. & Firing, E. (1997). Estimates of diapycnal mixing using ladcp and ctd data from i8s. *WOCE International Newsletter* **29**, 29–42.
158. Naveira Garabato, A., Polzin, K., King, B., Heywood, K. & Visbeck, M. (2004). Widespread intense turbulent mixing in the southern ocean. *Science* **303**, 210–213.
159. Marshall, D. & Naveira Garabato, A. (2008). A conjecture on the role of bottom-enhanced diapycnal mixing in the parameterization of geostrophic eddies. *Journal of Physical Oceanography* **38**, 1607.
160. Nikurashin, M. & Ferrari, R. (submitted). Radiation and dissipation of internal waves generated by geostrophic flows impinging on small-scale topography: Theory. *Journal of Physical Oceanography* .
161. Molemaker, M., McWilliams, J. & Yavneh, I. (2005). Baroclinic instability and loss of balance. *Journal of Physical Oceanography* **35**, 1505–1517.
162. Simmons, H. L., Jayne, S. R., St-Laurent, L. C. & Weaver, A. J. (2004). Tidally driven mixing in a numerical model of the ocean general circulation. *Ocean Modelling* **6**, 245–263.
163. Koch-Larrouy, A. *et al.* (2007). On the transformation of Pacific Water into Indonesian Throughflow Water by internal tidal mixing. *Geophysical Research Letters* **34**, L04604.
164. Jayne, S. (2009). The impact of abyssal mixing parameterizations in an ocean general circulation model. *Journal of Physical Oceanography* **39**, 1756–1775.

165. Bryan, K. & Lewis, L. (1979). A water mass model of the world ocean. *Journal of Geophysical Research* **84**, 2503–2517.
166. Polzin, K. L. (2004). Idealized solutions for the energy balance of the finescale internal wavefield. *Journal of Physical Oceanography* **34**, 231–246.
167. Bühler, O. & Muller, C. (2007). Instability and focusing of internal tides in the deep ocean. *Journal of Fluid Mechanics* **588**, 1–28.
168. Muller, C. & Bühler, O. (2009). Saturation of the internal tides and induced mixing in the abyssal ocean. *Journal of Physical Oceanography* **39**, 20772096.
169. St. Laurent, L. & Garrett, C. (2002). The role of internal tides in mixing the deep ocean. *Journal of Physical Oceanography* **32**, 2882–2899.
170. St. Laurent, L. C., Simmons, H. & Jayne, S. (2002). Estimating tidally driven energy in the deep ocean. *Geophysical Research Letters* **29**, 2106–2110.
171. Laurent, L. C. S. & Nash, J. D. (2004). An examination of the radiative and dissipative properties of deep ocean internal tides. *Deep Sea Research Part II: Topical Studies in Oceanography* **51**, 3029 – 3042.
172. Koch-Larrouy, A., Madec, G., Iudicone, D., Atmadipoera, A. & Molcard, R. (2008). Physical processes contributing to the water mass transformation of the Indonesian throughflow. *Journal of Physical Oceanography* **58**, 275–288.
173. Koch-Larrouy, A., Madec, G., Blanke, B. & Molcard, R. (2008). Water mass transformation along the Indonesian throughflow in an OGCM. *Journal of Physical Oceanography* **58**, 289–309.
174. Koch-Larrouy, A., Lengaigne, M., Terray, P., Madec, G. & Masson, S. (2009). Tidal mixing in the Indonesian seas and its effect on the tropical climate system. *Climate Dynamics* in press.
175. Zhai, X., Greatbatch, R., Eden, C. & Hibiya, T. (2009). On the loss of wind-induced near-inertial energy to turbulent mixing in the upper ocean. *Journal of Physical Oceanography* **in press**.
176. Maltrud, M. & McClean, J. (2005). An eddy resolving global  $1/10^\circ$  ocean simulation. *Ocean Modelling* **8**, 31–54.
177. Semtner, A. J. & Mintz, Y. (1977). Numerical simulation of the Gulf Stream and mid-ocean eddies. *Journal of Physical Oceanography* **7**, 208–230.
178. Roberts, M. J. & Marshall, D. (1998). Do we require adiabatic dissipation schemes in eddy-resolving ocean models? *Journal of Physical Oceanography* **28**, 2050–2063.
179. Griffies, S. M. & Hallberg, R. W. (2000). Biharmonic friction with a Smagorinsky viscosity for use in large-scale eddy-permitting ocean models. *Monthly Weather Review* **128**, 2935–2946.
180. Chassignet, E. P. & Garraffo, Z. Viscosity parameterization and the Gulf Stream separation. In Müller, P. & Henderson, D. (eds.) *From Stirring to Mixing in a Stratified Ocean*, Proceedings of the 12th 'Aha Huli'ko'a Hawaiian Winter Workshop, 37–41 (University of Hawaii at Manoa, 2001).
181. Hecht, M., Peterson, M., Wingate, B., Hunke, E. & Maltrud, M. Lateral mixing in the eddying regime and a new broad-ranging formulation. In Hecht, M. & Hasumi, H. (eds.) *Eddy resolving ocean models*, Geophysical Monograph 177, 339–352 (American Geophysical Union, 2008).
182. Fox-Kemper, B. & Menemenlis, D. Can large eddy simulation techniques improve mesoscale rich ocean models? In Hecht, M. & Hasumi, H. (eds.) *Eddy resolving ocean models*, Geophysical Monograph 177, 319–338 (American Geophysical Union, 2008).
183. Solomon, H. (1971). On the representation of isentropic mixing in ocean models. *Journal of Physical Oceanography* **1**, 233–234.
184. Gent, P. R., Willebrand, J., McDougall, T. J. & McWilliams, J. C. (1995). Parameterizing eddy-induced tracer transports in ocean circulation models. *Journal of Physical Oceanography* **25**, 463–474.
185. Greatbatch, R. J. & Lamb, K. G. (1990). On parameterizing vertical mixing of momentum in non-eddy resolving ocean models. *Journal of Physical Oceanography* **20**, 1634–1637.
186. Greatbatch, R. J. (1998). Exploring the relationship between eddy-induced transport velocity, vertical momentum transfer, and the isopycnal flux of potential vorticity. *Journal of Physical Oceanography* **28**, 422–432.
187. Ferreira, D. & Marshall, J. (2006). Formulation and implementation of a residual-mean ocean circulation model. *Ocean Modelling* **13**, 86–107.
188. Zhao, R. & Vallis, G. K. (2008). Parameterizing mesoscale eddies with residual and eulerian schemes, and a comparison with eddy-permitting models. *Ocean Modelling* **23**, 1–12.

189. Hecht, M. W., Holm, D. D., Petersen, M. R. & Wingate, B. A. (2008). The lans-alpha and leryay turbulence parameterizations in primitive equation ocean modeling. *Journal of Physics A-Mathematical and Theoretical* **41**.
190. Visbeck, M., Marshall, J. C., Haine, T. & Spall, M. (1997). Specification of eddy transfer coefficients in coarse resolution ocean circulation models. *Journal of Physical Oceanography* **27**, 381–402.
191. Treguier, A. M., Held, I. M. & Larichev, V. D. (1997). On the parameterization of quasi-geostrophic eddies in primitive equation ocean models. *Journal of Physical Oceanography* **27**, 567–580.
192. Danabasoglu, G. & Marshall, J. (2007). Effects of vertical variations of thickness diffusivity in an ocean general circulation model. *Ocean Modelling* **18**, 122–141.
193. Eden, C. & Greatbatch, R. (2008). Towards a mesoscale eddy closure. *Ocean Modelling* **20**, 223–239.
194. Eden, C., Jochum, M. & Danabasoglu, G. (2009). Effects of different closures for thickness diffusivity. *Ocean Modelling* **26**, 47–59.
195. Ferrari, R., McWilliams, J., Canuto, V. & Dubovikov, M. (2008). Parameterization of eddy fluxes near oceanic boundaries. *Journal of Climate* **21**, 2770–2789.
196. Danabasoglu, G., Ferrari, R. & McWilliams, J. (2008). Sensitivity of an ocean general circulation model to a parameterization of near-surface eddy fluxes. *Journal of Climate* **21**, 1192–1208.
197. Ferrari, R., Griffies, S., Nurser, A. & Vallis, G. (2009). A boundary-value problem for the parameterized mesoscale eddy transport. *Ocean Modelling* **in revision**.
198. Boccaletti, G., Ferrari, R. & Fox-Kemper, B. (2007). Mixed layer instabilities and restratification. *Journal of Physical Oceanography* **35**, 1263–1278.
199. Fox-Kemper, B., Ferrari, R. & Hallberg, R. (2008). Parameterization of mixed layer eddies. I: Theory and diagnosis. *Journal of Physical Oceanography* **38**, 1145–1165.
200. Fox-Kemper, B., Danabasoglu, G., Ferrari, R. & Hallberg, R. W. (2008). Parameterizing submesoscale physics in global models. *Clivar Exchanges* **13**, 3–5.
201. Thomas, L., Tandon, A. & Mahadevan, A. Submesoscale processes and dynamics. In Hecht, M. & Hasumi, H. (eds.) *Eddy resolving ocean models*, Geophysical Monograph 177, 17–38 (American Geophysical Union, 2008).
202. Lapeyre, G., Klein, P. & Hua, B. L. (2006). Oceanic restratification forced by surface frontogenesis. *Journal of Physical Oceanography* **36**, 1577–1590.
203. Thomas, L. N. & Ferrari, R. (2008). Friction, frontogenesis, and the stratification of the surface mixed layer. *Journal of Physical Oceanography* **38**, 2501–2518.
204. Capet, X., McWilliams, J. C., Molemaker, M. J. & Shchepetkin, A. F. (2008). Mesoscale to submesoscale transition in the California current system. Part II: Frontal processes. *Journal of Physical Oceanography* **38**, 44–64.
205. Capet, X., McWilliams, J. C., Molemaker, M. J. & Shchepetkin, A. F. (2008). Mesoscale to submesoscale transition in the California current system. Part III: Energy balance and flux. *Journal of Physical Oceanography* **38**, 2256–2269.
206. Smagorinsky, J. Some historical remarks on the use of nonlinear viscosities. In Galperin, B. & Orszag, S. A. (eds.) *Large Eddy Simulation of Complex Engineering and Geophysical Flows*, 3–36 (Cambridge University Press, 1993).
207. Gent, P. & McWilliams, J. (1996). Eliassen-Palm fluxes and the momentum equations in non-eddy-resolving ocean circulation models. *Journal of Physical Oceanography* **26**, 2539–2546.
208. Leith, C. E. (1996). Stochastic models of chaotic systems. *Physica D* **98**, 481–491.
209. Large, W. G., Danabasoglu, G., McWilliams, J. C., Gent, P. R. & Bryan, F. O. (2001). Equatorial circulation of a global ocean climate model with anisotropic horizontal viscosity. *Journal of Physical Oceanography* **31**, 518–536.
210. Smith, R. D. & McWilliams, J. C. (2003). Anisotropic horizontal viscosity for ocean models. *Ocean Modelling* **5**, 129–156.
211. Jochum, M. *et al.* (2008). Ocean viscosity and climate. *Journal of Geophysical Research* **114** C06017, doi:10.1029/2007JC004515.
212. Wunsch, C. & Ferrari, R. (2004). Vertical mixing, energy, and the general circulation of the ocean. *Annual Reviews of Fluid Mechanics* **36**, 281–314.

213. Rudnick, D. *et al.* (2003). From tides to mixing along the hawaiian ridge. *Science* **301**, 355–357.
214. Gille, S. T., Speer, K., Ledwell, J. & Naveira Garabato, A. (2007). Mixing and stirring in the southern ocean. *EOS* **88**, 382–383.
215. Wunsch, C. & Stammer, D. (1995). The global frequency-wavenumber spectrum of oceanic variability estimated from TOPEX/POSEIDON altimetric measurements. *Journal of Geophysical Research* **100**, 24,895–24,910.
216. Wunsch, C. (1997). The vertical partition of oceanic horizontal kinetic energy and the spectrum of global variability. *Journal of Physical Oceanography* **27**, 1770–1794.
217. Stammer, D. (1997). Global characteristics of ocean variability estimated from regional TOPEX/POSEIDON altimeter measurements. *Journal of Physical Oceanography* **27**, 1743–1769.
218. Holloway, G. (1986). Estimation of oceanic eddy transports from satellite altimetry. *Nature* **323**, 243–244.
219. Stammer, D. (1998). On eddy characteristics, eddy transports, and mean flow properties. *Journal of Physical Oceanography* **28**, 727–739.
220. Kushner, P. J. & Held, I. M. (1998). A test, using atmospheric data, of a method for estimating oceanic eddy diffusivity. *Geophysical Research Letters* **25**, 4213–4216.
221. Smith, K. S. & Vallis, G. K. (2001). The scales and equilibration of midocean eddies: freely evolving flow. *Journal of Physical Oceanography* **31**, 554–570.
222. Karsten, R. & Marshall, J. (2002). Constructing the residual circulation of the ACC from observations. *Journal of Physical Oceanography* **32**, 3315–3327.
223. Scott, R. B. & Wang, F. (2005). Direct evidence of an oceanic inverse kinetic energy cascade from satellite altimetry. *Journal of Physical Oceanography* **35**, 1650–1666.
224. Zhai, X., Greatbatch, R. & Kohlmann, J.-D. (2008). On the seasonal variability of eddy kinetic energy in the gulf stream region. *Geophysical Research Letters* **35**, L24609 doi:10.1029/2008GL036412.
225. Smith, K. S. & Marshall, J. (2009). Evidence for enhanced eddy mixing at middepth in the southern ocean. *Journal of Physical Oceanography* **39**, 50–69.
226. Freeland, H. *et al.* Argo a decade of progress. In Hall, J., Harrison, D. & Stammer, D. (eds.) *Proceedings of the OceanObs09 Conference: Sustained Ocean Observations and Information for Society, Venice, Italy, 21-25 September 2009*, vol. 2 (ESA Publication WPP-306, 2010).
227. Oschlies, A. (2002). Improved representation of upper-ocean dynamics and mixed layer depths in a model of the north atlantic on switching from eddy-permitting to eddy-resolving grid resolution. *Journal of Physical Oceanography* **32**, 2277–2298.
228. de Boyer Montégut, C., Madec, G., Fischer, A. S., Lazar, A. & Iudicone, D. (2004). Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology. *Journal of Geophysical Research-Oceans* **109**.
229. Dong, S., Sprintall, J., Gille, S. T. & Talley, L. (2008). Southern ocean mixed-layer depth from argo float profiles. *Journal of Geophysical Research-Oceans* **113**.
230. Fox-Kemper, B. & Ferrari, R. (2008). Parameterization of mixed layer eddies. Part II: Prognosis and impact. *Journal of Physical Oceanography* **38**, 1166–1179.
231. Wajsovicz, R. C. (1986). Free planetary waves in finite-difference numerical models. *Journal of Physical Oceanography* **16**, 773–789.
232. Haidvogel, D. B. & Beckmann, A. *Numerical Ocean Circulation Modeling* (Imperial College Press, London, 1999).
233. Gates, W. (1993). AMIP: The Atmosphere Model Intercomparison Project. *Bulletin of the American Meteorological Society* **73**, 1962–1970.
234. Barnier, B. Forcing the ocean. In Chassignet, E. P. & Verron, J. (eds.) *Ocean Modeling and Parameterization*, vol. 516 of *NATO ASI Mathematical and Physical Sciences Series*, 45–80 (Kluwer, 1998).
235. Large, W. & Yeager, S. Diurnal to decadal global forcing for ocean and sea-ice models: the data sets and flux climatologies. NCAR Technical Note: NCAR/TN-460+STR (CGD Division of the National Center for Atmospheric Research, 2004).
236. Röske, F. (2006). A global heat and freshwater forcing dataset for ocean models. *Ocean Modelling* **11**, 235–297.
237. Large, W. G. & Yeager, S. (2009). The global climatology of an interannually varying air-sea flux data set. *Climate Dynamics* **33**.

238. Griffies, S. M. *et al.* (2009). Coordinated Ocean-ice Reference Experiments (COREs). *Ocean Modelling* **26**, 1–46.
239. Böning, C. W., Scheinert, M., Dengg, J., Biastoch, A. & Funk, A. (2006). Decadal variability of subpolar gyre transport and its reverberation in the north atlantic overturning. *Geophysical Research Letters* **33**, doi:10.1029/2006GL026906.
240. Doney, S. C., Yeager, S., Danabasoglu, G., Large, W. & McWilliams, J. (2007). Mechanisms governing interannual variability of upper-ocean temperature in a global ocean hindcast simulation. *Journal of Physical Oceanography* **37**, 1918–1938.
241. Biastoch, A., Böning, C. W., Getzlaff, J., Molines, J.-M. & Madec, G. (2008). Causes of interannual-decadal variability in the meridional overturning circulation of the midlatitude north atlantic ocean. *Journal of Climate* **21**, 6599–6615.
242. Liu, J. & Curry, J. (2006). Variability of the tropical and subtropical ocean surface heat flux during 1989–2000. *Geophysical Research Letters* **33**, L05706, doi:10.1029/2005GL0024809.
243. Killworth, P. D., Smeed, D. & Nurser, A. (2000). The effects on ocean models of relaxation toward observations at the surface. *Journal of Physical Oceanography* **30**, 160–174.
244. Bernie, D., Woolnough, S., Slingo, J. & Guilyardi, E. (2005). Modeling diurnal and intraseasonal variability of the ocean mixed layer. *Journal of Climate* **18**, 1190–1202.
245. Danabasoglu, G. *et al.* (2006). Diurnal coupling in the tropical oceans of CCSM3. *Journal of Climate* **19**, 2347–2365.
246. Bernie, D., Guilyardi, E., Madec, G., Slingo, J. & Woolnough, S. (2007). Impact of resolving the diurnal cycle in an ocean-atmosphere gcm. part 1: A diurnally forced ogcm. *Climate Dynamics* **29**, 575–590.
247. Bernie, D. *et al.* (2008). Impact of resolving the diurnal cycle in an ocean-atmosphere gcm. part 2: A diurnally coupled ogcm. *Climate Dynamics* **31**, 909–925.
248. Stine, A., Huybers, P. & Fung, I. (2009). Changes in the phase of the annual cycle of surface temperature. *Nature* **457**, 1133–1138.
249. Lewis, M., Carr, M., Feldman, G., Esaias, W. & McClain, C. (1990). Influence of penetrating solar radiation on the heat budget of the equatorial Pacific ocean. *Nature* **347**, 543–545.
250. Rosati, A. & Miyakoda, K. (1988). A general circulation model for upper ocean simulation. *Journal of Physical Oceanography* **18**, 1601–1626.
251. Nakamoto, S. *et al.* (2001). Response of the equatorial pacific to chlorophyll pigment in a mixed layer isopycnal ocean general circulation model. *Geophysical Research Letters* **28**, 2021–2024.
252. Murtugudde, R., Beauchamp, J., McClain, C., Lewis, M. & Busalucchi, A. (2002). Effects of penetrative radiation on the upper tropical ocean circulation. *Journal of Climate* **15**, 470–486.
253. Manizza, M., Le Quere, C., Watson, A. & Buitenhuis, E. (2005). Bio-optical feedbacks among phytoplankton, upper ocean physics and sea-ice in a global model. *Geophysical Research Letters* **32**, doi:10.1029/2004GL020778.
254. Sweeney, C. *et al.* (2005). Impacts of shortwave penetration depth on large-scale ocean circulation and heat transport. *Journal of Physical Oceanography* **35**, 1103–1119.
255. Wetzel, P. *et al.* (2006). Effects of ocean biology on the penetrative radiation in a coupled climate model. *Journal of Climate* **19**, 3973–3987.
256. Lengaigne, M. *et al.* (2007). Influence of the oceanic biology on the tropical pacific climate in a coupled general circulation model. *Climate Dynamics* **28**, 503–516.
257. Anderson, W., Gnanadesikan, A., Hallberg, R., Dunne, J. & Samuels, B. (2007). Impact of ocean color on the maintenance of the Pacific cold tongue. *Geophysical Research Letters* **34**, L11609, doi:10.1029/2007GL030100.
258. Gnanadesikan, A. & Anderson, W. (2009). Ocean shortwave absorption and the ocean general circulation in a coupled climate model. *Journal of Physical Oceanography* **39**, 314–332.
259. Legnaigne, M. *et al.* (2009). Bio-physical feedbacks in the arctic ocean in an earth system model. *Geophysical Research Letters* in revision.
260. Benitez-Nelson, C. R. & McGillicuddy, J., Dennis J. (2008). Mesoscale physical-biological-biogeochemical linkages in the open ocean: An introduction to the results of the e-flux and eddies programs - preface. *Deep-Sea Research Part II-Topical Studies In Oceanography* **55**, 1133–1138.
261. Oschlies, A. Eddies and upper-ocean nutrient supply. In Hecht, M. & Hasumi, H. (eds.) *Ocean Modeling in an Eddy Regime*, vol. 177, 115–130 (AGU Geophysical Monograph Series, 2008).

262. Klein, P. & Lapeyre, G. (2009). The Oceanic Vertical Pump Induced by Mesoscale and Submesoscale Turbulence. *Annual Review of Marine Science* **1**, 351–375.
263. Doney, S. *et al.* (2004). Evaluating global ocean carbon models: The importance of realistic physics. *Global Biogeochemical Cycles*, **18**.
264. Gnanadesikan, A. & Toggweiler, J. (1999). Constraints placed by silicon cycling on vertical exchange in general circulation models. *Geophysical Research Letters* **26**, 1865–1868.
265. Gnanadesikan, A. *et al.* (2004). Oceanic ventilation and biogeochemical cycling: Understanding the physical mechanisms that produce realistic distributions of tracers and productivity. *Global Biogeochemical Cycles* **18**.
266. Siegel, D., Fields, E. & Buesseler, K. (2008). A bottom-up view of the biological pump: Modeling source functions above ocean sediment traps. *Deep Sea Research I* **55**, 108–127.
267. Bishop, J., Wood, T., Davis, R. & Sherman, J. (2004). Robotic observations of enhanced carbon biomass and export at 55S during SOFeX. *Science* **304**, 417–420.
268. England, M. H. & Maier-Reimer, E. (2001). Using chemical tracers to assess ocean models. *Reviews of Geophysics* **39**, 29–70.
269. Willey, D. *et al.* (2004). Global oceanic chlorofluorocarbon inventory. *Geophysical Research Letters* **31**, L01303, doi:10.1029/2003GL018816.
270. Key, R. *et al.* (2004). A global ocean carbon climatology: results from GLODAP. *Global Biogeochemical Cycles* **18**, GB4031.
271. Dutay, J.-C. *et al.* (2004). Evaluation of OCMIP-2 ocean models' deep circulation with mantle helium-3. *Journal of Marine Systems* **48**, 15–36.
272. Gnanadesikan, A., de Boer, A. & Mignone, B. A simple theory of the pycnocline and overturning revised. In *Ocean Circulation: Mechanisms and Impacts*, vol. 173 of *Geophysical Monograph Series*, 19–32 (American Geophysical Union, 2007).
273. Kuhlbrodt, T. *et al.* (2007). On the driving processes of the Atlantic meridional overturning circulation. *Reviews of Geophysics* **45**, doi:10.1029/2004RG000166.
274. Stommel, H. (1961). Thermohaline convection with two stable regimes of flow. *Tellus* **13**, 224–228.
275. Rooth, C. (1982). Hydrology and the ocean circulation. *Progress in Oceanography* **11**, 131–149.
276. Bryan, F. (1986). High latitude salinity effects and interhemispheric thermohaline circulations. *Nature* **323**, 301–304.
277. Manabe, S. & Stouffer, R. J. (1988). Two stable equilibria of a coupled ocean-atmosphere model. *Journal of Climate* **1**, 841–866.
278. Delworth, T. L., Manabe, S. & Stouffer, R. J. (1993). Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model. *Journal of Climate* **6**, 1993–2011.
279. Griffies, S. M. & Tziperman, E. (1995). A linear thermohaline oscillator driven by stochastic atmospheric forcing. *Journal of Climate* **8**, 2440–2453.
280. Greatbatch, R. & Peterson, K. (1996). Interdecadal variability and oceanic thermohaline adjustment. *Journal of Geophysical Research* **101**, 20467–20482.
281. Colin de Verdière, A. & Huck, T. (1999). Baroclinic instability: A wavemaker for oceanic interdecadal variability. *Journal of Physical Oceanography* **29**, 865–892.
282. Delworth, T. & Greatbatch, R. (2000). Multidecadal thermohaline circulation variability driven by atmospheric surface flux forcing **13**, 1481–1495.
283. Baehr, J., Hirschi, J., Beismann, J.-O. & Marotzke, J. (2004). Monitoring the meridional overturning circulation in the North Atlantic: a model-based array design study. *Journal of Marine Research* **62**, 283–312.
284. Cunningham, S. A. *et al.* (2007). Temporal variability of the Atlantic meridional overturning circulation at 26.5N. *Science* **317**, 935–938.
285. Little, C., Gnanadesikan, A. & Hallberg, R. (2007). Large-scale oceanographic constraints on the distribution of melting and freezing under ice shelves. *Journal of Physical Oceanography* **38**, 2242–2255.
286. Russell, J., Dixon, K., Gnanadesikan, A., Stouffer, R. & Toggweiler, J. (2006). Southern ocean westerlies in a warming world: Propping open the door to the deep ocean. *Journal of Climate* **19**, 6381–6390.
287. Toggweiler, J. & Russell, J. (2008). Ocean circulation in a warming climate. *Nature* **451**, 286–288.
288. Anderson, R. *et al.* (2009). Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO<sub>2</sub>. *Science* **323**, 1443–1448.
289. Böning, C. W., Dispert, A., Visbeck, M., Rintoul, S. & Schwarzkopf, F. (2008). The response of the antarctic circumpolar current to recent climate change. *Nature Geoscience* **1**, 864–869.

290. Hallberg, R. & Gnanadesikan, A. (2006). On the role of eddies in determining the structure and response of the wind-driven southern hemisphere overturning: Results from the Modeling Eddies in the Southern Ocean (MESO) project. *Journal of Physical Oceanography* **36**, 2232–2252.
291. Russell, J., Stouffer, R. & Dixon, K. (2006). Inter-comparison of the southern ocean circulations in the ipcc coupled model control simulations. *Journal of Climate* **19**, 4560–4575.