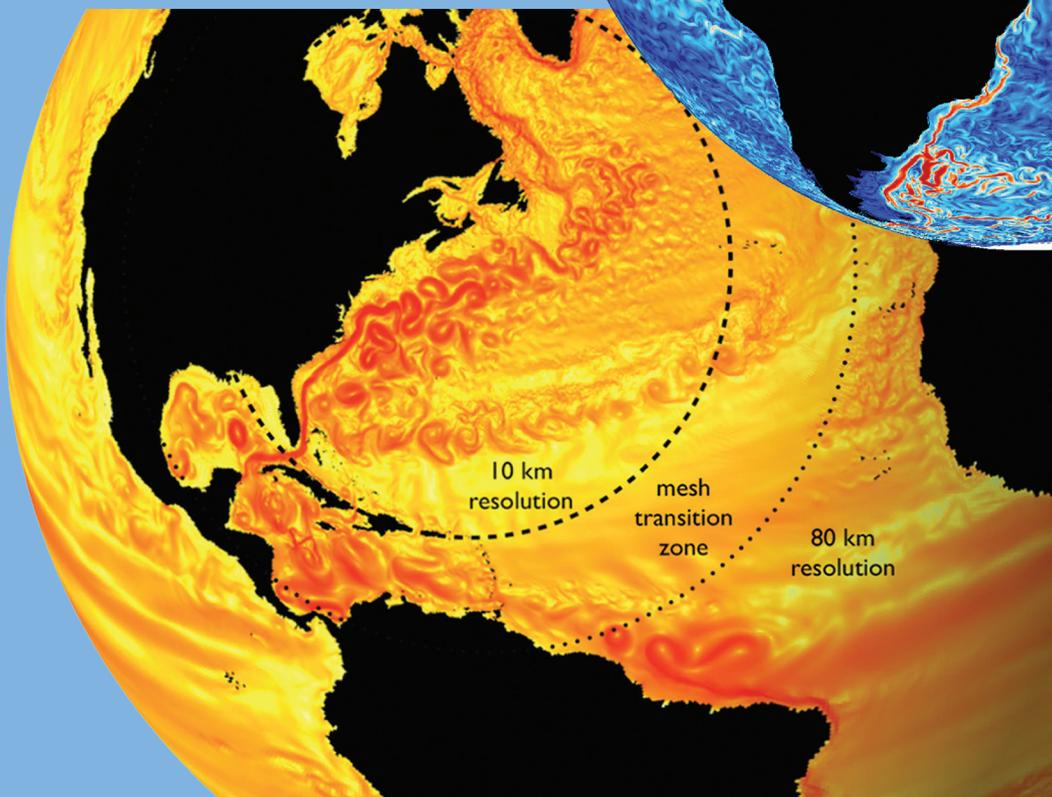
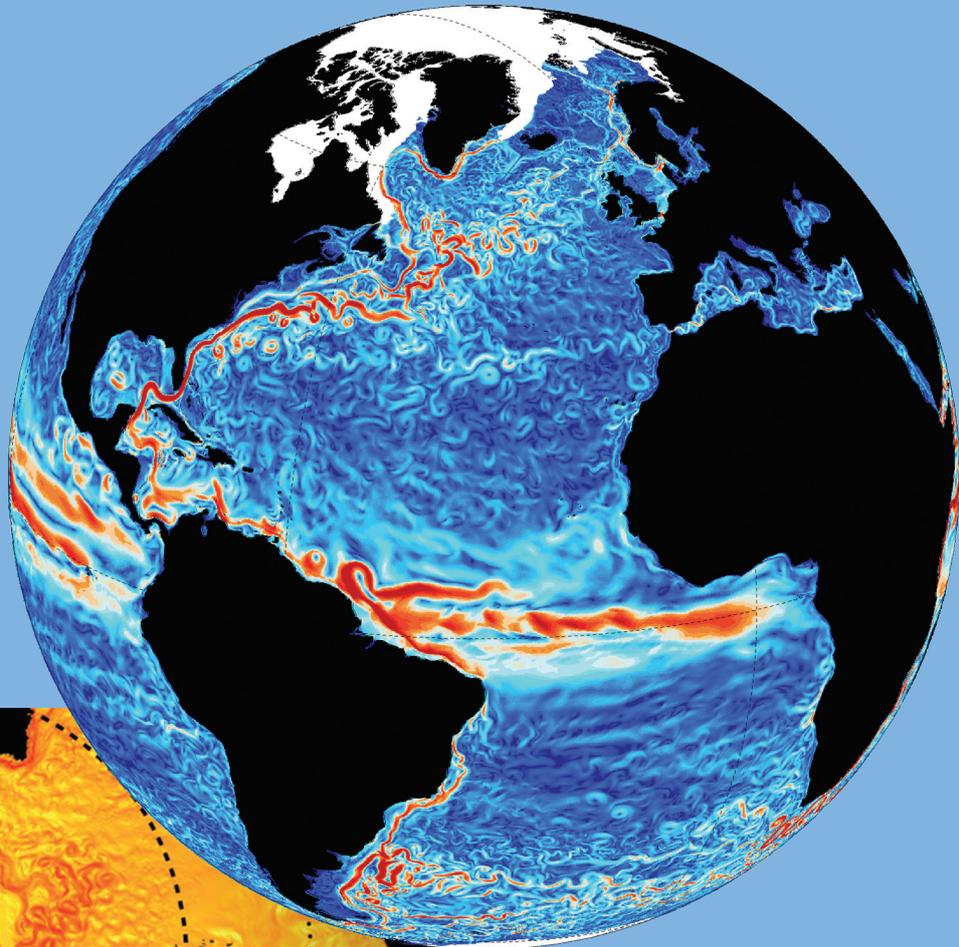




# Exchanges

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# Principles and advances in subgrid modelling for eddy-rich simulations

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## 1. Introduction

One of the challenges of global and large-scale ocean modelling is the comparatively small scale of the turbulent features in comparison to the dimension of the ocean basins. The largest of these features, mesoscale eddies, usually form from hydrodynamic instabilities near the first baroclinic Rossby deformation scale. Recent evidence from coupled models and satellites shows many significant effects, such as eddy effects on air-sea coupling (Bryan et al., 2010; Frenger et al., 2013), near-inertial coupling (e.g., Jochum et al., 2013), and low-frequency eddy-driven decadal variability (e.g., Berloff et al., 2007). Parameterisations of the mechanisms behind these processes are likely to be complex or are presently unknown, and it is this sort of dynamics that drive interest in high-resolution climate modelling (e.g., McClean et al., 2011; Delworth et al., 2012). These coupled models come at a much greater cost, and there is more difficulty in diagnosing causal linkages between model physics and model biases, than even high-resolution ocean-only models. Thus, it is paramount to reduce the amount of tuning and number of unjustified parameters in these eddying ocean models.

Figure 1 shows the progression in resolution of the ocean model component of coupled Earth System Models reported in the IPCC versus the range of Rossby scales across the globe (Chelton et al., 1998). Computational capability increases exponentially: Moore's (1965) scaling predicts a resolution doubling every 6 years. However, the highest-resolution coupled Atmosphere-Ocean Models (AOMs) and Earth System Models (ESMs) refine slower due to increasing model complexity and numerical challenges (6.9 and 10.2 years to double resolution, respectively). Much higher resolution models exist for limited-duration basin or coastal applications, but they generally do not include the coupled dynamics mentioned and cannot be grouped with these other model types. The extrapolation in Figure 1 predicts decades to a century before climate models routinely fully-resolve mesoscale and submesoscale turbulence, with the majority of ESMs at only eddy-permitting resolution at most latitudes.

When models are eddy-permitting or even eddy-rich, it is important to tailor optimal subgridscale (SGS) closures to the physical and numerical setting. The tradition in coarse-resolution models is to fully parameterise all eddy effects, and in fine resolution models to turn off all physical parameterisations of eddy effects and minimise numerical closures (e.g., Delworth et al., 2012). Hallberg (2013) suggests that the scale at which this transition occurs can be selected dynamically and automatically during the course of a simulation, so that changes in stratification and latitude are handled smoothly in a physically-meaningful manner. Similarly, Fox-Kemper et al. (2011) feature a gridscale-dependent amplification factor for a submesoscale physics parameterisation, which extinguishes the parameterisation if mixed layer depth and stratification change so as to make the parameterised features resolved.

The key distinction between coarse- and fine-resolution in terms of subgridscale closure is whether there is a scale separation between the gridscale and the largest eddy

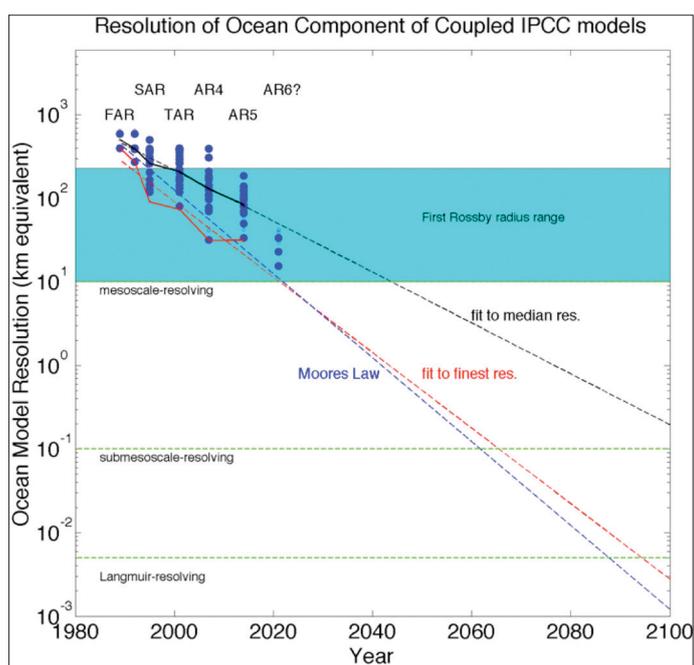


Figure 1: Estimate of the effective nominal horizontal resolution of ocean model components for primary baseline and climate change scenarios as reported in the IPCC reports by year of publication. Exponential fits to the median, finest-resolution, and a Moore's (1965) law estimate are shown; the doubling of resolution occurs every 10.2, 6.9, and 6 years, respectively. Standards for "resolving" turbulence types and the first baroclinic deformation radius range (Chelton et al. 1998) are also indicated. Sixth assessment report (AR6) high-resolution estimates based on present prototypes are indicated, but not fitted.

scale. If there is a separation, then closures depend only parametrically on flow variables and are independent of fine adjustments to the gridscale, and thus the closures are called parameterisations. If there is no scale separation between the resolved flow and the largest eddy scale, then the model falls into the category of Large Eddy Simulations (LES). Ocean models where the gridscale lies between the largest mesoscale eddy scale and the smallest can be called Mesoscale Ocean Large Eddy Simulations (MOLES). For example, complete resolution of baroclinic instability on

all vertical modes (mesoscale and submesoscale) remains distant in global models (based on Figure 1), and so part of the eddy effects should still be included in a MOLES closure. In MOLES, the closures, or subgridscale (SGS) models, should depend on fine adjustments of the gridscale versus physically-important scales (be "scale-aware") and may take advantage of sampling the statistics of the resolved eddies to inform the SGS model (be "flow-aware"). The combination of the two guiding principles of SGS models avoids "double-counting" the largest eddies in both the resolved flow and the parameterisation. When a scale separation exists in some regions and not in others, a hybrid of the parameterisation extinguishing approach exemplified by Hallberg (2013) can be used to transition to MOLES SGS models.

Scale-aware and flow-aware SGS modelling began with Smagorinsky's (1963) viscosity scaling for three-dimensional (3d) turbulence in an inertial range. The upper panel of Figure 2 schematises his approach. Energy injection is expected to occur on large scales and then cascade through an inertial range to smaller scales. In Kolmogorov's (1941) idealization, energy flux ( $\epsilon$ ) through the scales of the inertial range ( $k_L$ ) is constant and independent of the viscosity, which becomes important only at a smaller viscous scale ( $k_D$ ). If grid resolution is insufficient to resolve the small scale dissipation processes, a larger value of viscosity is selected that depends upon the gridscale and the resolved flow of energy toward small scales. While there are sound objections to Kolmogorov's idealization, it is a useful framework for estimating the scaling laws needed for SGS models. By ensuring consistency, Smagorinsky devised a robust, scale-aware formulation of viscosity that has been used extensively. Early viscosity scalings for eddy-rich modelling followed Smagorinsky in selecting flow dependence on the deformation rate (Griffiths and Hallberg, 2000; Willebrand et al., 2001), and depend on a power of the gridscale and a tunable coefficient to provide harmonic or biharmonic viscosities at all latitudes.

However, the large-scale ocean is too shallow and stratified to have 3d turbulence. Two-dimensional (2d) and quasigeostrophic (QG) turbulence, more applicable to the ocean dynamics on scales near the deformation radius, feature two conserved quantities - energy and enstrophy in 2d, or energy and potential enstrophy in QG - which lead to two distinct inertial ranges (Kraichnan, 1967; Charney, 1971; Figure 2 lower panel). The flow of energy to the largest scales depends on an energy flux, while the flow toward the smallest scales depends instead on a (potential) enstrophy flux. Energy and enstrophy injection into this cascade is considered to take place at intermediate scales where hydrodynamic instabilities are most active - i.e., near the appropriate deformation radius in mesoscale and submesoscale eddy-rich models. Leith (1996) and Fox-Kemper and Menemenlis (2008) suggest and implement, respectively, a SGS closure for eddy-rich ocean models based on the enstrophy cascade in 2d turbulence. It is important to note differences from the Smagorinsky-school closures: the flow-awareness differs and the scale-awareness differs. The Leith viscosity is proportional to the vorticity gradient instead of the deformation rate, so it is one differential order higher. The Leith harmonic viscosity depends on the third power of gridscale instead of the first (Willebrand et al., 2001) or second (Smagorinsky, 1963); and similarly is one to two powers of gridscale larger for biharmonic viscosity (Fox-Kemper and Menemenlis, 2008).

The differences in flow-awareness and scale-awareness make the Leith scaling more scale selective than the

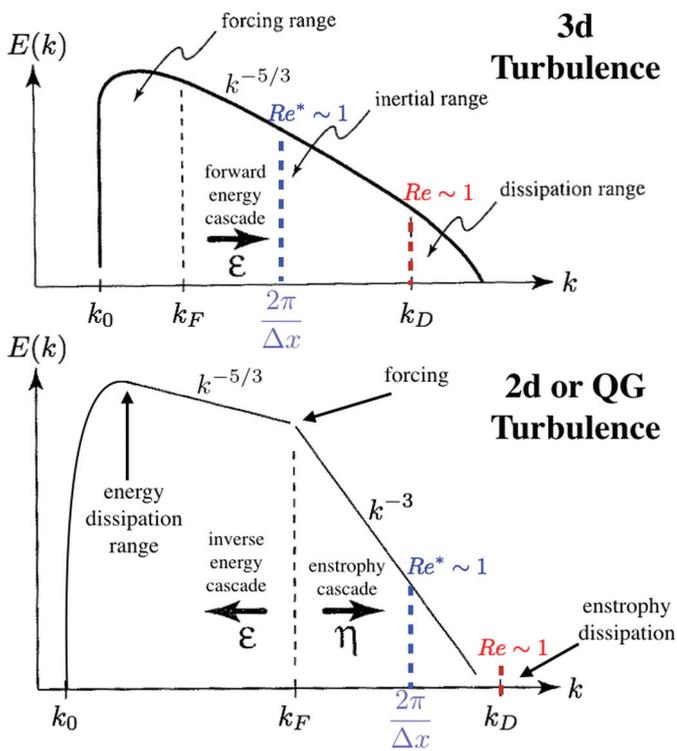


Figure 2: Comparison of the inertial range theories of Kolmogorov, Kraichnan, and Charney for inertial ranges in 3d (upper), 2d, and QG (lower) turbulence.

Smagorinsky scaling. Additional scale-selectivity was a goal of both Smagorinsky-school studies, which provoked the choice of biharmonic operators. Testing at variable resolutions in 2d turbulence simulations (Pietarila Graham and Ringler, 2013) and 3d Boussinesq models in the QG regime (Bachman and Fox-Kemper, in prep) show that the degree of scale selectivity in the Leith scheme (harmonic and biharmonic) is accurate across a broad range of MOLES resolutions. For example, recent global simulations using the MITgcm at 1/54th of a degree (Menemenlis, pers. comm.) used the same biharmonic Leith scheme described for a 1/8th degree run (Fox-Kemper and Menemenlis, 2008) without retuning of any viscosity or diffusivity parameters.

It is difficult to observe ocean eddy statistics, especially covariances such as eddy fluxes, directly (e.g., Flierl and McWilliams, 1977, find that long timeseries are needed). Thus, while it would be ideal to base closures directly on observations, it is unlikely to be possible. Indirect effects of eddies and other results of eddy fluxes (boundary current separation location, sea surface height variance, meridional heat transport, mooring velocity statistics, etc.) are presently the best way to check high-resolution models for consistency.

## 2. Choosing a subgrid-scale (SGS) Model for Mesoscale Ocean Large Eddy Simulations (MOLES)

In building or selecting SGS closures for high-resolution models, there are a number of considerations. Many difficulties can be avoided, and some choices bring many benefits.

A brief list of avoidable issues follows. Many SGS closures seek to avoid competition for energy sources and double-counting of eddy effects between the eddies that are resolved and handled by the SGS closure. Any parameters

that arise in the SGS scheme should be dimensionless, so that as gridscale or physical setting changes the models can be applied without retuning. The dimensionless parameters, and the theoretical and physical motivation for the closure, should not be extended for use when the gridscale dynamics do not resemble those of the motivating principles. Nor should the parameters be tweaked to remove discrepancies that stem from new physical mechanisms. In oceanography, where the very weak abyssal turbulence preserves the distinctive mix of tracers in each for centuries, spurious mixing by SGS closures and numerical errors is a worry (Veronis, 1975; Griffies et al., 2000; Ilicak et al. 2012).

Careful selection of SGS closures heeds the following list of good practices. Clear theoretical and physical motivation for the closure should exist, and a clear statement of these principles should be available. With such a basis, ready improvement and evaluation of the model is straightforward. Where known asymptotic limits exist, a connection should be made, with the approach to this limit following observed scaling relationships. The SGS scheme should have robust numerical performance, so that linear and nonlinear instabilities are sufficiently damped (preferably in approximation to how they are damped in the real world). Closures can draw from past experience, but continual evaluation and comparisons versus contrasting or new ideas in controlled tests (e.g., idealised experiments where a high-resolution “truth” run is possible) reveals many deficiencies that are easily addressed. These tests are only meaningful if it is possible for a closure to fail (Popper, 1998). Convergence of key metrics with increasing resolution is ideal as a meaningful test. Finally, as already emphasised, in MOLES SGS models, scale- and flow-awareness are advantageous in the ocean, where heterogeneity of flow and gridscale are common.

MOLES differ substantially from traditional LES in the dynamical regime present at the gridscale. LES methods usually assume isotropic, homogeneous turbulence in models with unity aspect ratio. MOLES feature 2d or quasi-2d turbulence in a strongly anisotropic gridscale, which may or may not match the anisotropy of the flow features. For example, does the Burger number of the grid respect the  $f/N$  value everywhere in the flow? Furthermore, in stratified, rotating flow viscosity is not enough: eddy effects have been shown to resemble viscosity (Smagorinsky, 1963), diffusivity (Redi, 1982), advection (Gent & McWilliams, 1990), and dispersion (Nadiga & Bouchet, 2011), among other possibilities.

## 3. Recent Progress on SGS Models

Bachman and Fox-Kemper (in prep) improve on the ideas in Fox-Kemper and Menemenlis (2008) in a practical SGS model combining the best aspects of the Leith 2d scheme and the Gent-McWilliams and Redi parameterisations. This adiabatic model very naturally converts between 2d and QG scalings as the flow evolves, and specifies matched eddy-induced viscosity, diffusivity, and advection. This scale- and flow-awareness based on gridscale Rossby, Richardson, and Burger numbers tends toward a 2d enstrophy cascade or a QG potential enstrophy cascade as the regime transitions from 2d to QG physics.

Recent work on parameterisations (Smith and Marshall, 2009; Ferrari and Nikurashin, 2010; Abernathey et al., 2010, 2013; Eden, 2011; Fox-Kemper et al., 2013; Reckinger et al., in prep) emphasises enhancement or suppression of

eddy mixing by flow and stratification effects, such as shear dispersion and critical layers. An exciting aspect of MOLES is that such effects may not need to be explicitly addressed - they will naturally arise from the resolved eddy interactions and therefore be carried into the SGS model. This conjecture is testable in future diagnoses of MOLES. Of course, the cost of global MOLES means that new parameterisations of these processes for coarse-resolution models will be used in most models for decades at least.

Proposing stochastic closures has also been active recently (Grooms and Majda, 2013; Porta Mana and Zanna, 2014; Jansen and Held, 2014). These models are naturally combined with MOLES closures, as has long been the case in LES stochastic backscatter schemes (e.g., Leith, 1990).

Other approaches to MOLES SGS modelling show promise in 2d and QG models. Chen et al. (2011) update the Sadourny (1975) anticipated potential vorticity method to scale-awareness. Nadiga and Bouchet (2011) show equivalence between LES methods in the 2d turbulence or MOLES regime. San and Staples (2011, 2013) adapt image-processing techniques as SGS models. Pietarila Graham and Ringler (2013) perform an excellent comparison of many of these models in an idealised 2d turbulence setting. Bachman and Fox-Kemper (in prep.) compare many of the common MOLES closures in 3d Boussinesq models in the QG regime.

## 4. Conclusions

Computational and theoretical advances have allowed the recent wave of realistic, high-resolution ocean modelling. Operational oceanographic models and high-resolution climate models are increasingly potentially important applications for society, but they are only as reliable and robust as the closures and numerics that they rely upon.

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# Large-scale ocean modelling on unstructured meshes

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## 1. Introduction

Ocean circulation modelling helps to gain understanding of the ocean's role in the changing climate. Most modelling studies are performed with traditional ocean circulation models formulated on structured meshes, which warrants numerical efficiency. The complexity of basin geometry and the need to incorporate eddy motions on various scales, or the need to include physical processes that involve small scales (such as overflows or coastal upwelling zones) serve as motivation to studies at increasingly refined meshes. Such high-resolution simulations require immense computational resources and storage. Rather commonly, the focus of simulations is on a particular area, and in such a case resolution in structured mesh models can be refined locally through nesting in order to spare resources (see, e. g. Debreu and Blayo, 2008). Nesting is available, for example, with NEMO and ROMS, and many models use it routinely in a build-in form.

A novel approach is offered by models formulated on unstructured meshes. While such models are common in coastal studies where geometrical complexity of coastlines and the need to resolve estuaries leave hardly any other choice, these models are only starting to be applied to simulate large-scale circulation. Unstructured meshes provide multi-resolution functionality and can accommodate multiple areas of arbitrary form with refined resolution, as dictated by practical tasks. Additionally, unstructured meshes can be aligned with coastlines or the continental break. This approach is offered by Finite-Element Sea-ice Ocean circulation Model (FESOM) (Wang et al., 2008, 2014) and MPAS-Ocean (Ringler 2013), and other developments, such as ICON (see ICON website) or the new core at AWI (Danilov 2012).

Compared to traditional nesting, the main advantage of using unstructured meshes is their unlimited refinement factor, lack of spurious reflections because of smooth transitions and consistent solution, and the ease of using: refinement is only the matter of mesh design. Their main drawback is their larger computational load per degree of freedom, and the fact that their time step is defined by the smallest element. Although unstructured-mesh models remain slower than their structured-mesh counterparts, at least one finite-volume implementation lags only by a factor about 3 (see Ringler et al., 2013), which is fully acceptable