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Towards a Physical Understanding of the North Atlantic: A Review of Model Studies in an Eddying Regime

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Abstract. We survey progress in modeling of the North Atlantic Ocean since a set of reviews last appeared around a dozen years ago. Predictions that a threshold in resolution was yet to be crossed proved to be true: $1/10^\circ$ or higher-resolution models are now capable of producing Gulf Stream separation at the observed location of Cape Hatteras, and other features of the Gulf Stream/North Atlantic Current system are much more realistically represented. The surface expression of eddy kinetic energy agrees well between models and observations. Mesoscale eddies also invigorate the deep circulation, which in turn improves the mean circulation via enhanced current-topography interactions. The successful generation of these prominent features of the circulation, however, is found to depend sensitively on model configuration issues that are not yet fully understood. More generally, the North Atlantic basin remains a particularly well-observed region in which high-resolution models can be used to explore fundamental issues in physical oceanography, such as the manner in which the turbulent variability feeds back on the large scale mean circulation, and the related issue of the range of spatial and temporal scales required in order to adequately describe the circulation.

1. Introduction

Ocean modeling of the North Atlantic has crossed over a threshold into a regime in which the variability of the circulation is comparable to that which is observed. Longstanding biases in the mean circulation have to a great degree been corrected, suggesting a critical role of variability and non-linearities in determining the mean flow. The last set of review papers addressing modeling of the basin were published just over a decade ago (*Stammer and Böning* [1996], *Böning and Bryan* [1996], *Dengg et al.* [1996]), as models were approaching that threshold. Our aim here is to survey more recent developments that have contributed to our emerging understanding of the complex circulation of the North Atlantic.

Early theoretical work was naturally focused on the mean circulation, in particular the Gulf Stream. An early map showing the Gulf Stream was drawn by the most important physical scientist of his day, Benjamin Franklin (*Stommel* [1965]); awareness of this strong current presented an advantage to American captains attempting to slip through the British naval blockade during the American Revolution. The elegant work of *Stommel* [1948] explained the intensification of the Gulf Stream and other western boundary currents as arising not from just rotation, but from rotation of a spherical planet (the β effect), bringing a first and still critical level of understanding to that portion of the gyre not addressed by the theory of *Sverdrup* [1947]. Following on to Stommel's insight into the intensification of western boundary currents *Munk* [1950] presented an understanding of the viscous forces which regulate that intensification. These earlier theoretical works were linear, and are therefore limited by the neglect of the advection of relative vorticity in the boundary current.

The modern recognition of the tremendous degree of oceanic variability required more extensive observations. Early maps of eddy energy were derived from ship drift data (*Wyrtki et al.* [1976]), while XBT data sets indicated the generation of eddies in regions of strong shear (*Dantzler* [1976], *Dantzler* [1977]).

Much of the initial study of the influence of mesoscale variability was focused on the North Atlantic, as it was the best sampled ocean basin, with a strong source of shear instability in the Gulf Stream. Other characteristics of the basin include its extensive span in latitude, with exchange of waters across the North Atlantic Sill. It is relatively compact in longitude, raising the influence of continental and mid-basin topography. The North Atlantic Current forms the most poleward penetration of any of the subtropical gyres of the World Ocean, at least in its modern configuration of the Holocene; evidence from ocean sediment cores suggests that it followed an eastward drift to the Mid-Atlantic Ridge at the Last Glacial Maximum (*Robinson et al.* [1995]). A much discussed feature of the northern basin on climate time scales, which may be related at some level to changes in the path of the North Atlantic Current, is the variability in deep water formation and meridional overturning (*Broecker et al.* [1985], *Rahmstorf* [2002]). The basin not only presents a context in which to develop our understanding of physical oceanography, but also presents a challenge to the understanding of prominent modes of climate variability, a topic which we touch on through discussion of the North Atlantic Current. We expect the relevance of mesoscale eddy feedback on mean North Atlantic circulation, and the oceanic response to changes in forcing, to be the subject of research over the coming years.

Early model-based research into the role of mesoscale eddy variability in Atlantic-like domains made use of idealized geometries. Using a flat-bottomed, rectangular domain with two layers on a β-plane, *Holland and Lin* [1975] found strong feedback of mesoscale eddies on the mean circulation, and in particular on the deep flow. Whereas *Holland and Lin* [1975] primarily studied eddy generation through baroclinic

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instability, *Robinson et al.* [1977] focussed on barotropic instability in a five level primitive equation model at 40 km resolution, again with an idealized flat-bottomed domain. *Semtner and Mintz* [1977] added an idealized continental slope to the problem, reporting on sensitivity to dissipation (and establishing an enduring preference for biharmonic closure over Laplacian at high spatial resolution), identifying the process of baroclinic-to-barotropic energy conversion as dominant in the western boundary region, and also producing the diagnosis of an equivalent eddy diffusivity.

The 1/3°, 18 level study of *Cox* [1985] was set in an idealized Atlantic domain. With the inclusion of bottom topography, the first realistic primitive equation model of the North Atlantic in an eddying regime was presented in *Böning* [1989], followed shortly by a factor of two horizontal refinement in *Böning and Budich* [1992]. At this point, in the early 1990's, ocean general circulation modeling had become a useful tool for the investigation of physical oceanography involving mesoscale variability, along with idealized process studies and physical theory.

As ocean general circulation modeling in an eddying regime became established, focus on the North Atlantic was maintained with the Community Modeling Effort (CME, *Bryan and Holland* [1989]). This period also saw groundbreaking research on the Southern Ocean, with the Fine Resolution Antarctic Model, *FRAM Group* [1991], and the nearly global study of *Semtner and Chervin* [1988] at 0.5° resolution with 20 levels, prognostic in the thermocline, with climatological restoring below. Careful analysis of the CME by *Treguier* [1992] confirmed and quantified the predominance of baroclinic-to-barotropic energy conversion.

Mean circulation was better simulated in some respects at resolutions as high as 1/6°, but in the Northwest Atlantic comparison with observations, even those from as early as *Iselin* [1936], still showed first-order biases in the North Atlantic Current and late separation of the Gulf Stream from the continental slope. These biases persisted even as *Böning et al.* [1995] showed that spurious cross-frontal mixing (the "Veronis effect", *Veronis* [1975]), associated with explicit horizontal diffusion, gave rise to a short circuiting of the meridional heat transport in models. Use of an isopycnal parameterization of eddy-driven tracer mixing (*Gent and McWilliams* [1990]) improved northward heat transport, but did not result in correction of the Gulf Stream or North Atlantic Current biases.

In the review of *Böning and Bryan* [1996], which was largely based on the CME simulations, it was demonstrated that despite persistence of low eddy energy levels over broad areas, models were capable of producing useful estimates of northward heat transport and amenable to detailed analysis of the underlying mechanisms. Their analysis of the heat transport showed that the thermohaline-driven meridional overturning dominates at low latitudes while the wind-driven gyre provides the stronger contribution at high latitudes. The details of this decomposition were found to depend on horizontal resolution, with resolution-dependent differences in the severity of the Veronis effect and path of the Gulf Stream Extension. In the context of idealized coupled experimentation, with ocean resolutions ranging from 4° down to 0.25°, *Fanning and Weaver* [1997] also discussed the dependence of oceanic poleward heat transport on resolution, emphasizing the need to improve representation of the Gulf Stream.

New insight was also being gained from observational data, both on a climate timescale and in a near-instantaneous sense. The insight of *Broecker et al.* [1985] that the rate of deep water formation in the North Atlantic had undergone periods of dramatic and sudden change was based on the Greenland ice core record. On the shorter end of the temporal spectrum, satellite based altimetry became established in the 1990's as one of the most important sources of data in oceanography with the very accurate measurements of the TOPEX/Poseidon mission (see *Wunsch and Stammer* [1995] for early spectral analysis of this altimetry).

The TOPEX/Poseidon mission produced a slightly revised estimate, relative to the earlier GEOSAT mission, for the apparently linear relationship between first internal Rossby radius R_1 and eddy length scale L_o, with $L_o = 1.7R_1 + 86km$ (*Stammer and Böning* [1996]). It is interesting to note that the 1/3° CME model produced realistic eddy length scales over the low-to-mid latitudes (*Stammer and Böning* [1992]), and the 1/6° version of the model produced fairly realistic eddy length scales even at higher latitudes (*Beckmann et al.* [1994]), and nevertheless further increases in resolution were required in order to finally produce a realistic Gulf Stream/North Atlantic Current system.

Beyond this slight revision of eddy length scale the TOPEX/Poseidon mission provided far more accurate estimates of variability over the less active regions of the ocean and allowed for greater discrimination of model fidelity. *Fu and Smith* [1996] made use of the data in the first detailed comparison of a global eddy-admitting ocean model with satellite altimetry, considering mean circulation, mesoscale variability and amplitude and phase of the annual cycle. The model variability in sea surface height was identified as being small by a factor of two (the model resolution was at 0.28°) with the deficiency attributed to insufficient resolution of the first internal Rossby radius.

The remote sensing data also provided further detail on the long-recognized problem of Gulf Stream separation and the path of the North Atlantic Current, allowing for quantitative comparison of model-produced variability with the surface expression of that variability in the sea surface height field over the entire extent of the current system. Another component of the current system included in this new and greatly clarified bird's eye view was the Azores Current, which also branches from the Gulf Stream around the Southeast Newfoundland Rise (*Klein and Siedler* [1989]). The more precise instruments better quantified levels of eddy kinetic energy in more quiescent regions, providing sufficient data from which to characterize the turbulent cascade, with frequency-dependent spectral decays largely confirming quasigeostrophic theory and significant anisotropy appearing only at the longer time scales associated with Rossby waves (*Stammer and Böning* [1996]). More recent analysis of *Eden* [2007] indicates the anisotropy to be restricted to latitudes below 30°, while the issue of turbulent cascade has also been revisited. The paper of *Scott and Wang* [2005] explores the question of why an inverse cascade is observed in surface altimetry, in accord with two-dimensional theory, despite the expectation that one should see a strong signature of the first baroclinic mode.

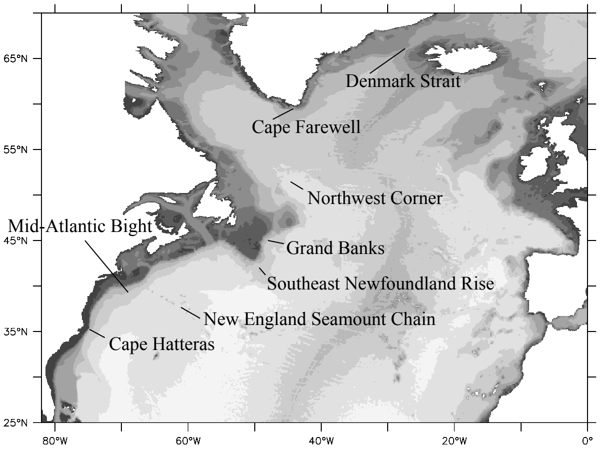


Figure 1. Topography of the North Atlantic with labeling of a number of the features referred to in the text.

While other model deficiencies mentioned above were recognized, the greatest attention in the mid-1990's was paid to the unsolved problem of Gulf Stream separation. *Dengg et al.* [1996] provided an excellent review of the subject, including a description of the Gulf Stream itself, describing the very stable location of separation at Cape Hatteras, the recirculation gyres and downstream development and the vertical and horizontal profiles of the Stream (see Figure 1 for the geography of the region). Modeling and theoretical work seemed to indicate that separation was not simply a function of one dominant physical process, but a more vexing balance of a number of important processes including the effects of advective nonlinearity, bathymetry (including bottom topography and coastline) and stratification (the possible role of the interaction of the Gulf Stream with the Deep Western Boundary Current was commented on but under appreciated).

Stammer and Böning [1996] and *Böning and Bryan* [1996] together provide a review of what we would now call "eddy-admitting" modeling of the North Atlantic. We proceed to survey progress since that point in time.

2. Gulf Stream Separation

As discussed by *Dengg et al.* [1996], various hypotheses based on a number of physical mechanism were presented to explain Gulf Stream separation in idealized circumstances. When idealization and limiting assumptions were relaxed, however, no single hypothesis seemed adequate to explain the ocean modeling failure of the Stream to separate at the observed location.

Even while refinement from 1° to 1/3° to 1/6° in the CME model failed to solve the Gulf Stream separation problem, producing instead a more pronounced anticyclonic stationary meander as the Stream overshot the observed separation point of Cape Hatteras in which much of the Stream's kinetic energy was dissipated, *Böning and Bryan* [1996] insightfully raised the likelihood that a modeling threshold was yet to be crossed as the first internal Rossby radius came within resolution.

This insight that the crossing of a threshold might be imminent was strongly suggested in the 1/6° study of *Chao et al.* [1996], and then proven out in the North Atlantic regional study of *Smith et al.* [2000]. The simulation was based on the same Parallel Ocean Program (POP; *Smith et al.* [1992], *Dukowicz and Smith* [1994]) used in the earlier 0.28° global simulation of *Maltrud et al.* [1998], but with an 0.1° mercator projection and 40 vertical levels spanning the Atlantic from approximately 20°S to somewhat beyond the North Atlantic Sill. Lateral boundary conditions were provided through restoring of hydrography to climatology within buffer zones, forcing was based on climatological means for heat flux and salinity with daily reanalysis winds. Within five or so years of spin-up kinetic energies had largely equilibrated and the Gulf Stream was seen to separate at the correct location of Cape Hatteras, without evidence of an anticyclonic meander at its separation from the coast, as shown in Plate 1 (taken from the newsletter piece of *Bryan and Smith* [1998]). The early 1/12° isopycnal model simulation of *Paiva et al.* [1999] also showed Gulf Stream separation at Cape Hatteras, providing a base state for the refinement of *Chassignet and Garraffo* [2001]. The results of *Paiva et al.* [1999] provided support for the importance of achieving a sufficiently inertial regime, as a prerequisite for separation to occur at Cape Hatteras.

A zonal-average of the model's first internal Rossby radius was shown in Figure 1 of *Smith et al.* [2000], reproduced here as our Figure 2. The act of "resolving" the Rossby radius is not as simple as maintaining a grid spacing less than or equal to the first internal Rossby radius. A span of several grid lengths is required if a numerical ocean model is to be capable of representing a feature. The eddy length scale is considerably larger than the Rossby radius, as mentioned above in reference to the paper of *Stammer and Böning* [1996], though it exhibits a linear dependence on the Rossby radius. It was not clear then, a priori, that 0.1° would prove sufficient to cross this threshold. Later investigation showed 0.1° to be barely adequate, with strong sensitivities to model configuration (*Chassignet and Garraffo* [2001], *Eden and Böning* [2002], *Maltrud and McClean* [2005], *Bryan et al.* [2007]), as discussed further in the next section. It is important to note that all of these works solve the same basic equations of fluid flow as in the now-classic paper of *Bryan* [1969], even if questions of numerical implementation remain consequential.

3. Model Sensitivities

Sensitivity studies in a strongly eddying regime have most often been conducted in a North Atlantic regional context, with sensitivity to lateral dissipation most thoroughly explored.

Most of our discussion in this section addresses modeling studies which include thermohaline as well as wind forcing, with dozens of levels or layers in the vertical. A satisfactory convergence study has yet to be attempted with such a model, but has been performed with an isopycnal model with up to six layers, without heat and fresh water forcings: The study of *Hurlburt and Hogan* [2000] focussed on the Gulf Stream region of the North Atlantic, and found great improvement in the pathway of the Gulf Stream and in the strength of abyssal flows when increasing resolution from 1/8° to 1/16°. Further refinement to 1/32° brought additional moderate improvement in these features. The authors see evidence of convergence at 1/64° resolution, in some regions, with more substantial dependence on resolution remaining evident in the region of the Grand Banks.

3.1. Sensitivity to Lateral Dissipation

Despite (or perhaps because of) the relatively thorough consideration that sensitivity to lateral dissipation has received, we address the question only briefly here. The topic is taken up in greater depth in *Hecht et al.* [2008], in this same volume, and is also touched on below, in section 5, as the North Atlantic Current and its penetration into the region of the Northwest Corner show particularly strong dependence on model configuration.

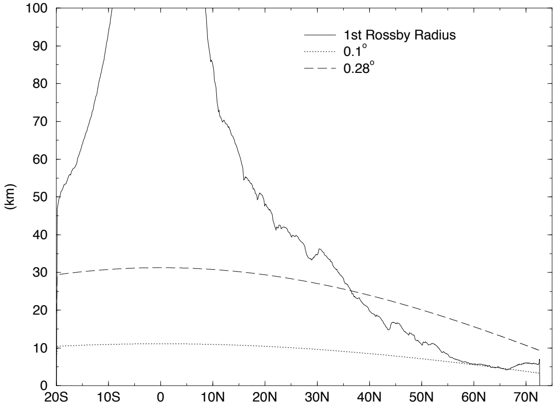


Figure 2. From *Smith et al.* [2000], showing the first baroclinic Rossby radius, temporally and zonally averaged from their 0.1° North Atlantic model, along with grid spacings of the 0.1° model and the 0.28° model of *Maltrud et al.* [1998].

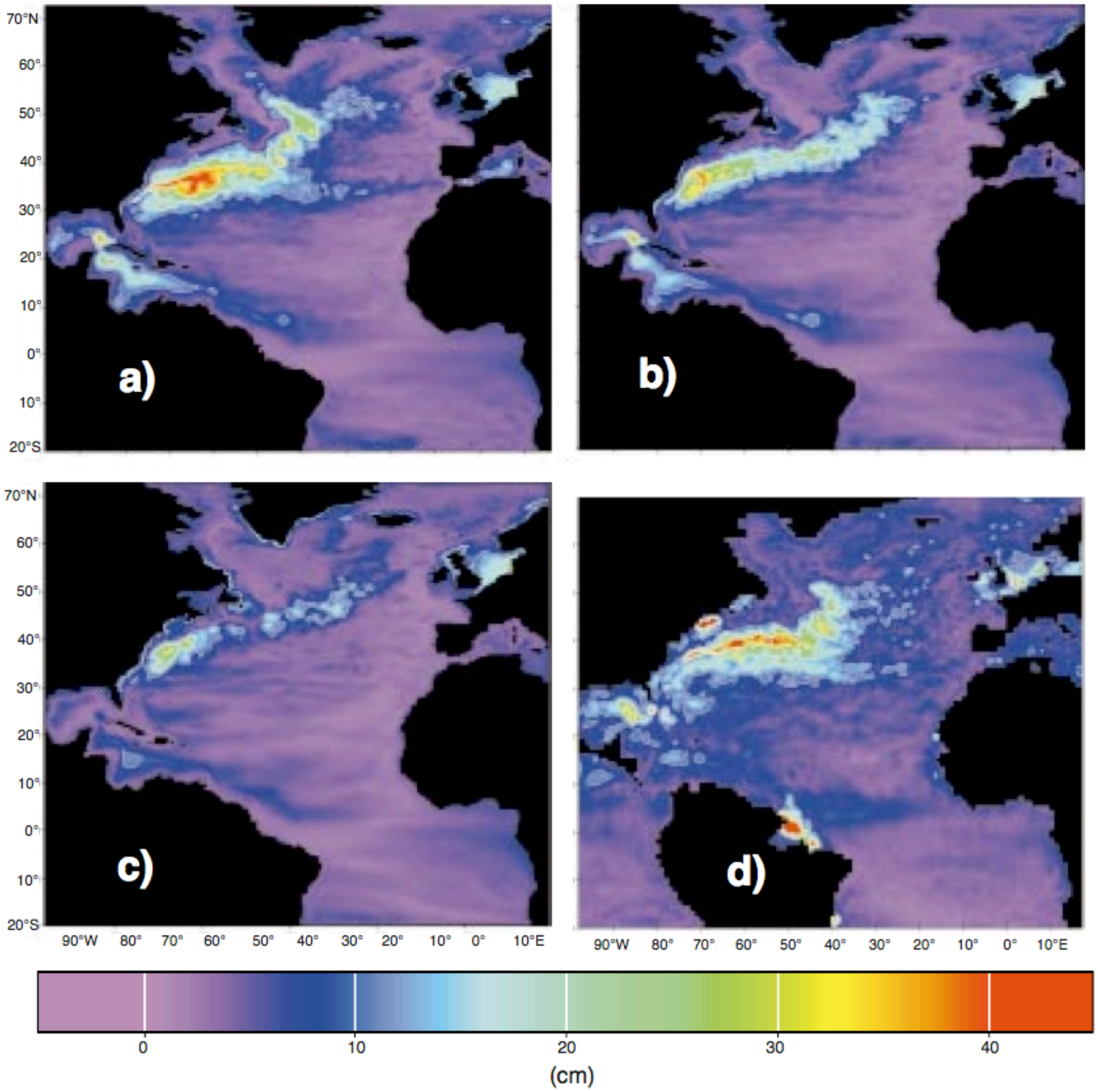


Plate 1. Sea surface height variability of North Atlantic models at resolutions of (a) 0.1°, (b) 0.2°, (c), 0.4°, and (d) for a blended ERS-TOPEX/POSEIDON altimetric product (*Le Traon and Ogor* [1998]). Figure taken from *Bryan and Smith* [1998].

The work of *Chassignet and Garraffo* [2001], however, deserves mention here as well as in *Hecht et al.* [2008]: They demonstrate an effective approach of combining Laplacian and biharmonic forms of dissipation at 1/12° in the layered Miami Isopycnal Coordinate Ocean Model (MICOM), in response to unsatisfactory results in their model with biharmonic dissipation alone. Also deserving mention is the work of *Smith and Gent* [2004], where they demonstrate that adequate levels of energy can be obtained with Laplacian viscosity if the anisotropic form of *Smith and McWilliams* [2003] is implemented with appropriate coefficients; they find improvement in water mass properties and meridional heat transport with the first use of an anisotropic form of the Gent-McWilliams isopycnal tracer mixing scheme (*Gent and McWilliams* [1990]). *Bryan et al.* [2007] identifies a relatively narrow range of acceptable values of biharmonic lateral mixing in the z-coordinate POP model, and further clarifies the roles of model resolution and lateral mixing with a limited study of grid convergence.

The range of acceptable values of lateral mixing coefficients is determined largely by the circulation the model produces, underlining the point that model configuration retains an aspect of tuning, even at the higher resolutions discussed in this paper. The models have not converged at 1/10° or 1/12°. The sensitivity to parameter values, particularly evident in the path of the Gulf Stream, is consistent with the findings of *Hurlburt and Hogan* [2000] in a slightly simplified context, where they reported needing resolutions of 1/16° and higher in order to produce a robust path.

3.2. Sensitivity to Topography

Barnier et al. [2006] attributed a part of their success in achieving some penetration of the North Atlantic Current into the Northwest Corner in their 1/4° global model to the use of a partial-step representation of topography (as explained in *Adcroft et al.* [1997]), along with the use of a more accurate advection scheme. The partial-step representation of topography has also been credited with significant improvement in Labrador Sea circulation, as discussed in section 5.

Further analysis of the model presented in *Barnier et al.* [2006] identifies the free-slip boundary condition as being essential to bringing out the improvements attributed to the formulation of advection, as those improvements were lost with reversion to the more commonly used no-slip boundary condition (*Penduff et al.* [2007]).

The use of partial steps allows for a smoother representation of bottom topography in regions of shallow slope. Explicit smoothing of topography was also mentioned in *Barnier et al.* [2006], motivated by the suggestive work of *Penduff et al.* [2002]. The impact of smoothing of topography probably merits further investigation in strongly eddying ocean modeling, where eddy-mean flow excitation of the deep flow would appear to raise the importance of more accurate representation of topographic interaction.

Horizontal grid discretization of course determines where the bottom depth is to be defined, and so is intertwined with topographic sensitivity. This point is touched upon in the following subsection.

3.3. Sensitivity to Domain

Following on the experience of *Smith et al.* [2000], a fully global 0.1° configuration of the POP model was developed by *Maltrud and McClean* [2005] with the expectation that the North Atlantic sector of the global model would look much as it did in the earlier regional simulation. It did not, and subsequent sensitivity studies were performed to understand and correct the somewhat late Gulf Stream separation and lack of penetration of the North Atlantic Current into the Northwest Corner within the global simulation (see their Figs. 7 and 12). These subsequent studies identified sensitivities to dissipation and to the use of partial cells, though neither was sufficient to fully correct the Gulf Stream/North Atlantic Current System (Bryan, Maltrud, McClean and Nakashiki, personal communication).

The lateral boundary conditions differed, of course, between regional and global configurations, as well as the discretization of the grid. The grid used by *Smith et al.* [2000] was a mercator projection (uniform aspect ratio, $dx/dy = 1$) of a latititude/longitude grid, whereas the global grid of *Maltrud and McClean* [2005] used a displaced pole in the northern hemisphere (see *Smith and Gent* [2002] and references therein), with the pole located in Hudson's Bay. The gridding of the southern hemisphere remained mercator while the gridding over the Northwest Atlantic departed greatly from that simpler projection, with grid cell aspect ratios departing signifcantly from one.

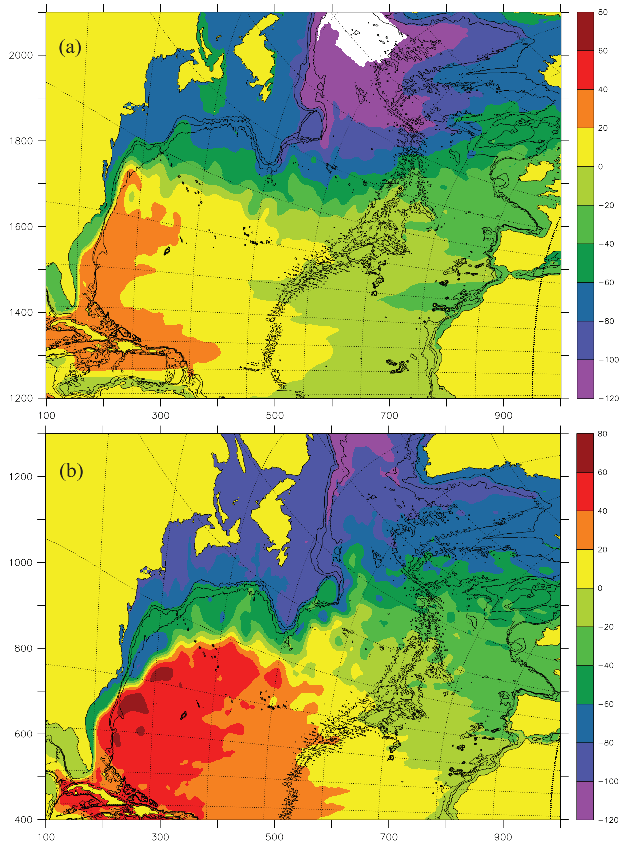


Plate 2. Time-averaged North Atlantic sea surface height from a global simulation on the 0.1° "displaced pole" grid of *Maltrud and McClean* [2005] (a), and on a specially configured North Atlantic regional version of the same grid designed to explore the sensitivity to lateral boundary conditions (b). Imposition of restoring lateral boundary conditions is sufficient to correct the separation of the Gulf Stream and the path of the North Atlantic Current. Notice that the map projection is in terms of model grid indices (i, j) showing the distortion associated with the grid. Lines of longitude and latitude are overlain in black.

Lateral boundary conditions in the regional model were set through restoring of potential temperature and salinity within buffer zones, whereas in the global configuration they were provided by the model itself in a more natural but less constrained fashion. A regional subdomain of the global model was extracted in order to evaluate the influence of lateral boundary conditions, with the location of lateral boundaries where restoring conditions were applied corresponding approximately to those of *Smith et al.* [2000]. As shown by *Hecht et al.* [2006], the constraint of restoring boundary conditions at the edges of the regional domain was sufficient to correct the Gulf Stream separation and send the North Atlantic Current into the Northwest Corner. This result is presented in our Plate 2, which also indicates the orientation of the underlying model grid lines of the displaced-pole grid.

Ongoing work in the 0.1° POP global model suggests the more satisfying result that the combined use of a more regular tripolar grid (*Smith and Gent* [2002]) and partial bottom cells (*Adcroft et al.* [1997]) is sufficient to correct the Gulf Stream separation and Northwest Corner, even using the full global domain (Maltrud, Bryan and Peacock, personal communication).

A number of the studies we discuss were performed with nested models (*Zhai et al.* [2004], *Dietrich et al.* [2004], *Greatbatch and Zhai* [2006], *Chanut et al.* [2007]), and the paper of *Capet et al.* [2008] in this same volume also presents a study performed with nesting. This approach has emerged from the domain of research and development, serving now to focus resolution on the region of interest in a particular study while allowing the lateral boundary conditions of that highly resolved domain to evolve with time, and, in the case of two way nesting, to adjust to the state of the more highly resolved subdomain.

3.4. Numerical Formulation

The requirement for resolution may, to some extent, be reduced by use of improved numerical schemes. In particular, *Dietrich et al.* [2004] make a case for the advantage of higher-order numerical treatments in the course of their exploration of the sensitivity of Gulf Stream separation to viscosity. Using the DieCAST model (*Dietrich et al.* [1997]), which has fourth-order accurate numerics (as contrasted with the second-order accurate numerics of most other models), they demonstrate separation at Cape Hatteras with sufficiently low dissipation, even with relatively moderate resolution of 1/6° in the separation (with boundary conditions provided by a 1/2° version of the model). They take particular note of the sensitivity of the Deep Western Boundary Current to viscosity, arguing for the importance of the mechanism of *Thompson and Schmitz* [1989]. It should be noted that DieCAST also differs from the other primitive equation models we discuss through its spatial discretization, and by the choice to allow static instability to form (the model is run without convective adjustment).

Barnier et al. [2006] provide support for the advantage of numerical schemes with physically based conservation properties, using the energy and estrophy-conserving scheme of *Arakawa and Lamb* [1981] in the momentum equations. The improvements they find in the Gulf Stream/North Atlantic Current within a 1/4° global model are jointly attributed to the transport scheme and the use of partial bottom cells (discussed above).

It should also be noted here that whereas conventional wisdom would suggest that advective errors become less of a problem with increasing resolution, this only applies in a straightforward way to laminar flow: *Griffies et al.* [2000] point out that increased diapycnal mixing of a spurious nature will be associated with increased eddy activity. The extent to which these advective errors may compromise eddy-resolving applications has never been directly addressed, and remains an important question.

Questions of numerical formulation tend to bring one back to the fundamental choice of model. Most prominent among questions to consider with respect to model is the vertical discretization, a subject which is treated extensively elsewhere, notably in the paper of *Griffies and Adcroft* [2008] within this volume. The choice that many modeling teams consider between level and isopycnal vertical coordinates determines the way in which diapycnal mixing is done. The result of *Chassignet and Garraffo* [2001], in which their isopycnal coordinate ocean model required a different form of lateral viscosity, relative to that of a z-coordinate model, in order to produce satisfactory results, represents one example of the consequences of choice of model.

4. Eddy Mixing and Parameterization

The North Atlantic has been studied in order to explore fundamental questions of physical oceanography as well as to understand the oceanography of the basin. Studies are relatively well constrained due to good observational data coverage, and the regional models require an order of magnitude fewer grid points than does a global model at comparable resolution. The North Atlantic offers particularly challenging tests of theoretical understanding, and of the application of that theoretical understanding to model formulation, in determining the balance of forces which result in the observed structure and path of the Gulf Stream and North Atlantic Current.

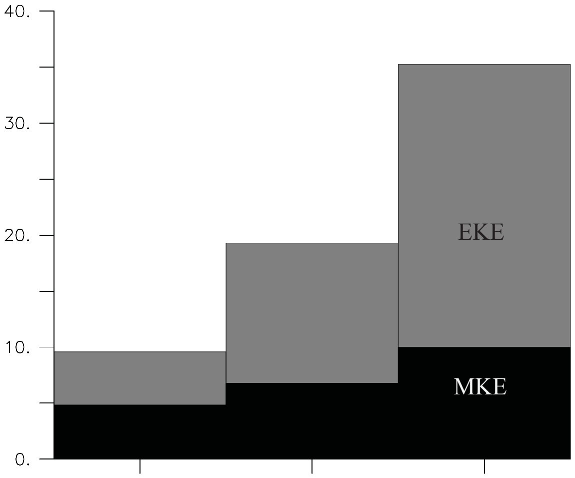


Figure 3. Kinetic energies, in units of cm^2/s^2, from three year time averages over the entire domain, from POP North Atlantic model simulations at horizontal grid resolutions of 0.4°, 0.2° and 0.1°, as indicated on the abscissa. The separation into mean kinetic energy (black) and eddy kinetic energy (grey) is done simply in terms of overall time mean and departure from that time mean.

The rapidly increasing level of eddy activity with resolution would appear to be a factor in obtaining Gulf Stream separation at the observed location of Cape Hatteras, as discussed in the preceding section, and in successful reproduction of many of the features discussed in the sections which follow. The rise of domain-averaged kinetic energy with resolutions ranging from 0.4° to 0.1° is illustrated with simulations of the POP model in Figure 3; comparison of sea surface height variability with observations derived from satellite-based altimetry, shown in Plate 1, strongly suggest the higher kinetic energy of the 0.1° case to be more realistic. The time-mean kinetic energy, indicated in black on Figure 3, rises modestly with resolution; the strong increase in total kinetic energy with resolution comes primarily from eddy kinetic energy. Spectral analysis of sea surface height variability, as in Figure 19 of *Smith et al.* [2000], supports the notion that a threshold has been crossed.

Attempts have been made over the past decade to directly diagnose eddy fluxes in order to better parameterize the role of eddies in non-eddy-resolving models, including those used for climate projection. We focus here on one recent paper, that of *Eden et al.* [2007], as an example of work on this important front in theoretical development. It also serves to illustrate the use of eddy-resolving models of the North Atlantic in the development of a theoretical understanding of the feedback of mesoscale variability on the mean flow, and in the parameterization of that interaction.

The so-called Gent-McWilliams parameterization of eddy mixing has proven to be one of the most significant advances not just in ocean modeling, but in climate modeling. The breakthrough of *Gent and McWilliams* [1990] was the recognition that eddies not only mix tracers along isopycnal surfaces, as had already been parameterized by *Redi* [1982], but that they also act on layer thickness, as in the release of potential energy associated with baroclinic instability, where downgradient diffusion of thickness occurs. The two diffusive coefficients, one for tracers and another for thickness, have most often been taken to be identical. In the adiabatic interior, the thickness diffusion can be recast as a transport term, bringing an eddy-induced component to the transport equations through what is referred to as the bolus velocity.

Diagnosis of a sign-definite isopycnal diffusivity was found to be problematic (*Rix and Willebrand* [1996], *Treguier* [1999]). *Bryan et al.* [1999] determined that the bolus velocity contains a significant rotational component, presenting a complication to the diagnosis of a downgradient thickness diffusivity from eddy flux data (either synthetic or observed).

In order to understand this statement regarding a rotational component of the eddy flux field, at least at a superficial level, some explanation is in order. Mesoscale eddy variability would be defined in terms of deviations from a temporal mean. Accordingly, eddy fluxes would appear in a tendency equation for the time-mean buoyancy, as, following the notation of *Eden et al.* [2007],

$$\bar{b}_t = -\bar{\mathbf{u}} \cdot \nabla \bar{b} - \nabla \cdot \mathbf{F} + \bar{Q} \tag{1}$$

where b is the buoyancy, Q is any diabatic forcing, an overbar indicates a time-averaging and $\mathbf{F}$ is the eddy flux in question.

Eqn. 1 is unchanged by the substitution of $\mathbf{F} + \nabla \times \theta$ in place of $\mathbf{F}$, where θ is an arbitrary vector field, as the divergence of the curl of a vector field is zero. This invariance of the tendency equation to inclusion of a rotational component is referred to as a "gauge" invariance, borrowing from the language of field theory. The consequence of choice of gauge, while irrelevant to the mean buoyancy budget, is however consequential to the diagnosis of a thickness diffusivity from eddy fluxes. *Fox-Kemper et al.* [2003] discusses the indeterminacy of a decomposition into rotational and divergent components, and also identifies diagnostics which remain invariant to the choice of decomposition.

Working in the 1/12° model of *Dengler et al.* [2004], *Eden et al.* [2007] confirm earlier findings of a very ambiguous sign of thickness diffusivity in the North Atlantic, before consideration of rotational fluxes (their Figure 3). A positive sign of thickness diffusivity would be expected under conditions of baroclinic instability, with release of APE (available potential energy). This release of APE can also be diagnosed directly from the correlation term $\overline{w'b'}$, which shows a pattern of APE release over most of the domain (their Figure 4), with the Gulf Stream region near and just downstream of Cape Hatteras being the one region in the mid-to-high latitudes in which the eddy buoyancy flux contributes broadly to an increase of APE, rather than a decrease. This observation implies that existing isopycnal mixing parameterizations cannot be expected to adequately model the subgrid-scale in this region.

The inconsistency between the patterns of $\overline{w'b'}$ and of thickness diffusivity diagnosed from eddy fluxes is associated with the gauge degree of freedom discussed above, and hence to the parameterization of that eddy flux as a downgradient diffusion. Whereas the usual bolus velocity of *Gent and McWilliams* [1990] is associated with the flux of buoyancy across contours of mean buoyancy, the rotational component of the eddy flux (the choice of which "fixes" the gauge) produces a bolus velocity along those contours of mean buoyancy, breaking the isotropy of the lateral mixing coefficient. The discrepancy between the sign of $\overline{w'b'}$ and that of thickness diffusivity diagnosed from eddy fluxes by *Eden et al.* [2007] is indicative of a need for some degree of spatially-dependent anisotropy in the isopycnal mixing formulation. This isotropy is found to be associated with westward advection, confirming zonal propagation of Rossby waves as a physical source of anisotropy in ocean mixing (*Smith and McWilliams* [2003]).

Considerable work has been done on the role of eddies in setting ocean stratification, particularly in the Southern Ocean (see for example *Karsten et al.* [2002]). The very recent paper of *Greatbatch et al.* [2007] builds on that of *Eden et al.* [2007], addressing the role of eddies in the determination of surface heat fluxes, with their analysis focussed on the Gulf Stream region.

5. The Northwest Atlantic

Mesoscale eddies mediate energy conversion between baroclinic and barotropic modes, and nowhere is this more evident than in the Northwest Atlantic. The degree to which the deeper flows in a model are energized through the inclusion of eddies appears to be critical in determining the character of the circulation in this region, with the biases of non-eddy-resolving models particularly extreme here.

5.1. The North Atlantic Current

The North Atlantic Current (NAC) has been described by *Rossby* [1996] as existing at a crossroads. The northward turn of the NAC around the Grand Banks and into the so-called Northwest Corner (see *Lazier* [1994] for a regional review) has already been mentioned at several points above, as it is a particularly elusive feature in ocean models. This remarkable northward excursion in fact represents the most poleward penetration of the near-surface waters of any of the subtropical gyres, and the absence of this northward penetration in non-eddy-resolving ocean models is responsible for some of the largest biases in sea surface temperature in ocean climate models, of the order of 5 to 10°C; this point is taken up in subsection 6.3.

Simulation of the North Atlantic Current depends, to a great extent, on the simulation of the Gulf Stream. It was understood as early as *Beckmann et al.* [1994] (see the summary of *Dengg et al.* [1996]) that the bias of a model Gulf Stream towards a strong anticyclonic meander north of Cape Hatteras results in excessive dissipation of the kinetic energy of the Stream. Models that exhibit this spurious, dissipative anticyclonic meander at separation also produce a poor description of total transport and structure of the Gulf Stream in the free jet region. *Bryan et al.* [2007] commented that they never saw penetration of the NAC into the Northwest Corner without Gulf Stream separation at Cape Hatteras in their sensitivity study.

Failure to separate at the observed location tends to correlate with a more surface-trapped Stream without the deep penetration of kinetic energy that would appear to be required for reattachment of the Gulf Stream at the Grand Banks and for the subsequent northward turn of the North Atlantic Current. This requirement for deep penetration of kinetic energy at the Grand Banks contrasts with the situation at Cape Hatteras, where the Deep Western Boundary Current serves to isolate the Gulf Stream from the influence of the underlying topography. The importance of barotropization of the Stream, of deep penetration of kinetic energy, can be taken as confirmation of the relevance of the early work of *Holland and Lin* [1975] and others on baroclinic instability in eddying ocean models. Eddy fluxes of potential vorticity can be related to a vertical transport of horizontal momentum, as shown by *Rhines and Holland* [1979], and as one might expect of a process which causes the circulation to become less variable with depth.

Penduff et al. [2006] noted insufficient vertical penetration of momentum in the CLIPPER model of the North Atlantic at 1/6° resolution. More recently, it has come to be understood by *Penduff et al.* [2007] that improved treatment of advection and the use of free-slip lateral boundary conditions are sufficient, when taken together, to raise levels of deep kinetic energy.

The importance of eddies in the establishment of the deep flow, and in the generation of pressure gradient torques which support the large scale mean circulation, will be addressed further in sections 6 and 7.

5.2. Labrador Sea

Käse et al. [2001] shows that in order to get a realistic mid-depth circulation, as elucidated by the observational analysis of *Lavender et al.* [2000], it is important to resolve the topography well. They make use of a previously mentioned partial step representation of topography (*Adcroft et al.* [1997]) in order to improve the resolution of the topographic slope, working at a resolution of 1/6°. *Myers and Deacu* [2004] also explored the impact of partial cells on the circulation of the Labrador Sea, and on the fresh water budget in particular, though at a lower resolution of 1/3°, finding that the Labrador Sea Water became saltier with partial bottom cells due to a strengthened Labrador Sea Counter-Current, with greater import of salty Atlantic waters and enhanced export of Labrador Sea waters to the Irminger Basin.

The large scale cyclonic circulation of the Labrador Sea causes isopycnal surfaces to dome in the interior of the basin, creating conditions under which deep convection can occur.

Eddies generated through a number of mechanisms act to reduce that doming and to restore stratification.

Spall [2004] considered the role of rim current eddies generated through baroclinic instability, commenting on the significant modification that occurs with departure from a flat bottomed topography. *Eden and Böning* [2002] discussed the generation of Irminger rings from Cape Desolation, off Southwest Greenland. Working in a realistic model at 1/12° horizontal resolution, and diagnosing energy transfer at depths between 100 and 400 meters, they attributed ring generation to barotropic instability. *Katsman et al.* [2004], in work related to that of *Spall* [2004], study this problem of restratification through boundary current-generated eddy fluxes in an idealized Labrador Sea, at 7.5 kilometer resolution and with 15 vertical levels. They confirm the finding of barotropic instability in the upper 400 meters off Cape Desolation, but also find baroclinic instability below this depth, raising the likelihood that Irminger rings are generated through a mixed instability. A third type of eddy in the Labrador Sea is generated at the edges of the convective patches themselves. These convective eddies may be thought of as sub-mesoscale, if rather deep-reaching, occurring within regions of very weak stratification and hence being of smaller size than what one would ordinarily refer to as a mesoscale eddy. Convective eddies and restratification following open-ocean convection have been studied by a number of authors, including *Visbeck et al.* [1996] and *Jones and Marshall* [1997]; these studies of convective eddies form the background for the current work on sub-mesoscale eddies discussed in two other papers within this volume (*Thomas et al.* [2008], *Fox-Kemper and Smyth* [2008]).

The three types of eddies we consider in the problem of Labrador Sea restratification are then:

1. Rim current eddies generated through baroclinic instability,
2. Irminger rings generated most likely through a mixed barotropic-baroclinic instability at Cape Desolation, and
3. convective eddies.

The role of all three types of eddies in restratification of the Labrador Sea has been examined by *Chanut et al.* [2007] in a realistic model with four kilometer discretization of the Labrador Sea, embedded within a 1/3° North Atlantic model. They resolve, at least marginally, even convective eddies, if only at the larger end of the spectrum.

In the region of deep convection, *Chanut et al.* [2007] found that rim current eddies flux enough heat laterally to explain the containment of deep convection in their model, setting up the large scale conditions under which convective eddies can work to restratify the water column immediately following deep convection, restricting the duration of events and the volume of water produced. They find Irminger rings only in the north of the basin, primarily poleward of about 60°N, although they have been observed to the south in the region of deep convection (*Lilly et al.* [2003]), where they can be expected to further contribute to restratification.

Consideration of the role of eddies in limiting deep convection in the Labrador Sea points to a limitation of Gent-McWilliams style parameterization of isopycnal tracer mixing. The generation of eddies may be described by local processes, but eddies propagate, and so their impacts do not necessarily remain local. A secondary issue is the limitation of the approach to the parameterization of baroclinic processes, with eddy generation through barotropic instability remaining unaddressed. While Gent-McWilliams isopycnal tracer mixing has been very successful on balance, we presume that these deficiencies which have yet to be addressed explain much of the benefit of explicit inclusion of the eddy field.

Waters formed in and exported from the Labrador Sea have observed densities in the range of $27.68 < \sigma_0 < 27.80$ (*Schott et al.* [2004]), and are particularly distinguished as being relatively fresh, with salinities of 34.95 psu and below. Treguier's analysis of model biases in Labrador Sea Water composition focuses in part on the underestimate of the salinity minimum shared by all four high-resolution models (*Treguier et al.* [2005]), arguing it to be the result of biases in horizontal transport, involving either transport from the eastern side of the basin or from much closer range, where the fresh water flux into the East Greenland Current is poorly represented. It bears mention that the salinity bias in question is nearly an order of magnitude less severe than that produced in low resolution, non-eddying models.

An important source of fresh water for the Labrador Sea is the throughflow from the Canadian Archipelago, which may require special attention to reproduce correctly, or even to represent at all, owing to the intricacy of the pathway. *Komuro and Hasumi* [2005] show that allowing for this throughflow makes for stronger Atlantic deep circulation, with the overflow waters from the GIN Sea spared from unrealistic dilution. *Oka and Hasumi* [2006] investigate the dependence of throughflow on resolution, which is understandably high; *Oka and Hasumi* [2004] explore the dependence of the North Atlantic deep circulation on fresh water forcing, finding the specification of river runoff at high northern latitudes to represent another critical factor. Fresh water forcing at high latitudes and the pathways taken by those waters are essential to the determination of meridional overturning, and hence to climate study, and yet they remain poorly known.

The Irminger Basin is the other place in the North Atlantic, south of the sills, where renewal of deep water may occur. In contrast to the situation in the Labrador Sea where deep water formation is well documented, deep water formation in the Irminger Basin has never actually been observed, but is inferred from circumstantial evidence (*Pickart et al.* [2003]). The properties of this presumed Irminger Sea Deep Water are close to those produced in the Labrador Sea. *Pickart et al.* [2003] argues that what has been considered to be LSW must be derived in part from the Irminger Basin.

Patterns of deep water formation in ocean general circulation models are infamously sensitive to the details of model configuration. This can be understood in part as due to the discontinuous, threshold behavior of the phenomenon: Small biases in wind or buoyancy forcing, parameterizations of mixing or representation of transport may be sufficient to trigger deep convection, or alternatively to erroneously suppress it. A certain degree of sensitivity to model configuration persists in the wintertime convective activity of eddy resolving ocean models, as seen in Plate 3. Partial step topography and anisotropic parameterizations of lateral mixing both tend to preserve the density of waters from the Denmark Strait overflow (the influence of the anisotropic lateral mixing parameterizations was documented in *Smith and Gent* [2004]). Evidently this tendency to preserve the density of the overflow waters that subsequently encircle the slope of the Northwest Atlantic translates into enhanced convection where that water of greater density becomes entrained in the strongly mixed portion of the water column. The extent of mixing in the Irminger Basin seen in panels (b) and (c) of Plate 3 is almost certainly unrealistic. A very high resolution modeling study, in the spirit of *Chanut et al.* [2007], could yet be applied to the broader region, perhaps bringing the analysis of the fresh water budget of *Treguier et al.* [2005] together with the analysis of overflow and entrainment of *Legg et al.* [2008] in order to better understand deep water formation in the Northwest Atlantic.

5.3. The Mann Eddy

If the North Atlantic Current exists at a crossroads then the Mann Eddy is not far from the center of that crossroads. Located at approximately 42°N and 43°W, *Rossby*

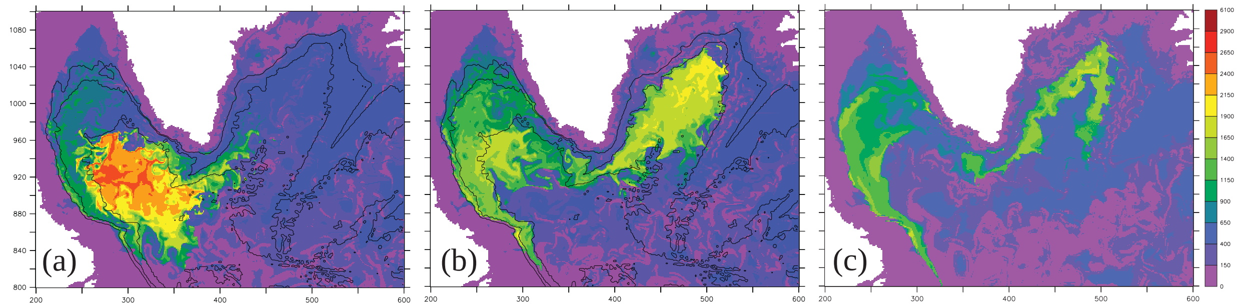


Plate 3. Mixed layer depths in the Labrador Sea and Irminger Basin in late March, 2000, for 0.1° configurations of the POP model, as in *Smith et al.* [2000] and *Bryan et al.* [2007], from cases (a) with biharmonic lateral dissipation and full step representation of topography, (b) with biharmonic lateral dissipation and partial step representation of topography, and (c) with partial steps and anisotropic formulations of isopycnal tracer mixing and viscosity, as in *Smith and Gent* [2004].

[1996] notes that the anticylonic Eddy contains the warmest waters at 1000m in the entire North Atlantic, a remarkable fact in light of its location at what would otherwise be the poleward limit of subtropical gyre waters.

The structure of the Eddy itself is not entirely clear from instantaneous inspection but emerges from a time averaging, as commented by *Smith et al.* [2000]. It is located towards the southern end of the set of topographically-constrained and more persistent meanders that the NAC forms as it flows northward around the Grand Banks (*Kearns and Paldor* [2000]), where some of the flow of NAC continues its eastward drift but much of it makes the northward turn, with some of that northward-tending water doubling back to the west as it forms the southern flank of the Eddy. Slightly to the south, closer to the Southeast Newfoundland Rise, the Azores Current, addressed in section 6, also branches off from the Gulf Stream and NAC.

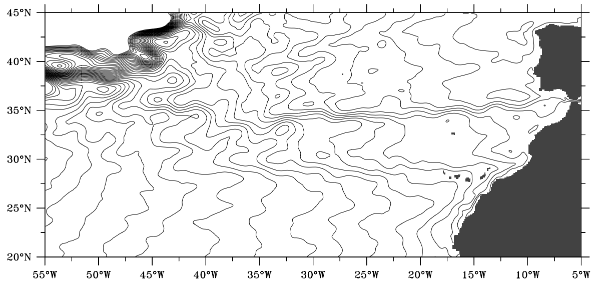
The temporal variability of the Mann Eddy presents a challenge to the observational description of the region; note that the section line analyzed in *Schott et al.* [2004] has its offshore end extending into the region occupied by the western flank of the Eddy. More complete description of the Mann Eddy could be accomplished through synthesis of model results and observations, where the temporal and spatial coverage of the model can contribute to the understanding of this remarkable feature found at the intersection of several major currents of the North Atlantic.

6. Gyre Structure and Basin-Wide Transport

The James test (*Seber* [1984]) provides a method by which to judge the level of agreement between model velocity fields and observational drifter data. In *McClean et al.* [2002], where the method is explained in an appendix, the authors apply the test to observed drifter data and Lagrangian floats in the 0.1° model of *Smith et al.* [2000] (but with the US Navy's daily NOGAPS wind forcing product and the K-profile parameterization of vertical mixing, *Large et al.* [1994]). The test was used to indicate agreement between model and observations at the 95% significance level. Agreement throughout the Labrador Sea was impressive, though the resolution of spatial binning and near-surface depth of inspection would not bring out the more intricate recirculations discussed above, in section 5. Discrepancies between the model circulation and observations were identified in the Mid-Atlantic Bight, parts of the Gulf Stream where the model produces an overly zonal flow, the North Atlantic Drift, where the North Atlantic Current flows after leaving the Northwest Corner, and in the Canary Current (off the northwest coast of Africa). In the more recent paper of *McClean et al.* [2006] the same test is applied to the North Atlantic regional model under daily surface heat fluxes (as opposed to the monthly heat flux climatology used in *Smith et al.* [2000]), with the most notable improvement being that of the Mid-Atlantic Bight.

While much of the more recent comparison of turbulent statistics from model and observations has made use of the surface expression through altimetry, *McClean et al.* [2006] also compared dispersion rates of numerical floats in the model of *Smith et al.* [2000] to those of the EUROFLOAT deployment, in which 21 floats followed the circulation at 1750 meter depth in the northeast Atlantic (*Speer et al.* [1999]). In the region covered by the floats, over the eastern half of the basin and extending into subpolar and subtropical gyres, one sees an initial period of linear dispersion of floats (average distance from center of mass of deployment proportional to elapsed time), as one would expect when the floats are following their initial outward trajectories. At later times, after the float trajectories become decorrelated,

(a) 0.1 (3/91–2/94)



(b) 0.1 (12/92)

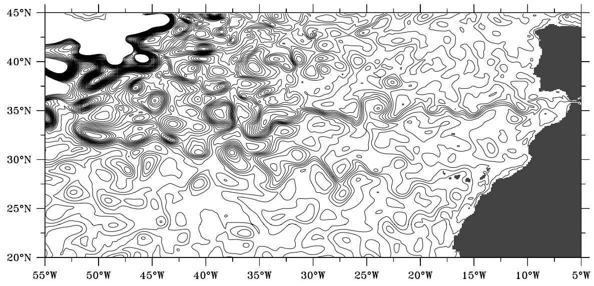


Figure 4. Sea surface height in the region of the Azores Current, from the 0.1° simulation of *Smith et al.* [2000], (a) from a three year time average, and (b) instantaneous.

the dispersion rate is slower, showing the square root dependence on time characteristic of a random walk (average distance from center of mass of deployment growing with $\sqrt{t}$). For both model and observations the transition between these dispersion regimes occurred between 10 and 20 days, a timescale characteristic of the mesoscale.

6.1. Azores Current

The Azores Current is the more southerly part of the Gulf Stream Extension. *Klein and Siedler* [1989] place the Current's origin off the Southeast Newfoundland Rise, near the Gulf Stream/North Atlantic Current juncture.

Smith et al. [2000] provided the first satisfactory comparison of the Azores Current from an ocean model with observations. One of their Azores plots is reproduced here as Figure 4. It is evident from this comparison of time-mean and instantaneous sea surface height fields that the variability of the flow is not necessarily small relative to the mean, posing a difficulty for any theoretical derivation relying on the ratio of u' to u as an expansion parameter.

From a study with three different models *New et al.* [2001] tells us that the Azores Current presents a front that tends to limit the southward extent of ventilated Eastern North Atlantic Water. Realistic strength of the Current may be important to the determination, in turn, of the potential vorticity and density structure of subtropical mode waters.

The intercomparison upon which *New et al.* [2001] was based deserves mention as a careful consideration of the impact of model formulation. Know as the Dynamo experiment, models based on z, isopycnal and sigma coordinates were configured at 1/3° eddy-permitting resolution. *Willebrand et al.* [2001] reported significant differences in large scale circulation which were attributed largely to differences in the overflow of the North Atlantic Sill.

An argument was also developed in *Jia* [2000], based on Dynamo results, for the importance of Mediterranean overflow and entrainment to development of the Azores Current. This argument has yet to be reexamined in a more energetic eddy-resolving context.

Stammer and Böning [1996], in concluding remarks, commented on weak or nonexistent Azores Front as among the most egregious deficiencies in model circulation. A number of authors, including *Böning and Bryan* [1996] and *Fu and Smith* [1996], had raised the possibility that crossing over into a regime with more adequate resolution of first internal Rossby radius would bring out such features. This speculation was confirmed when *Smith et al.* [2000] demonstrated that a strong Azores Current indeed emerges from such refinement. The establishment of a realistic Azores Current is found to depend sensitively on model configuration as well as on resolution, as with the previously described sensitivity of the Gulf Stream and North Atlantic Current; that the Azores Current shows a similar sensitivity should come as no surprise, knowing that its origin can be traced back to the "crossroads" of *Rossby* [1996], to the point at which the Gulf Stream rides over the Southeast Newfoundland Rise.

6.2. Recirculation Gyres

The barotropic stream function plots of *Bryan et al.* [2007], reproduced here as Figure 5, not only illustrate the sensitivity of Gulf Stream separation to resolution and lateral dissipation, but also illustrate the establishment of a strong and extensive Northern Recirculation Gyre with separation. *Zhang and Vallis* [2007] argue that vorticity production associated with downslope flow of the deep western boundary current gives rise to the Northern Recirculation Gyre, then causing Gulf Stream separation at the observed location of Cape Hatteras.

Zhai et al. [2004] present a "semi-diagnostic" method by which the influence of eddies may be ascertained while correcting for biases in large scale mean fields (their method is rooted in the "semi-prognostic" method of *Eden et al.* [2004], but with modification to avoid damping of eddies). They explore this method in the context of the northwest Atlantic, finding that the eddies are directly responsible for more than half of the transport of the Northern Recirculation Gyre, even at a model resolution of only 1/3°, apparently contributing to the establishment of the large scale bottom pressure torque that supports the gyre. The Northern Recirculation Gyre in turn is critical not only to the establishment of the offshore location of the free jet but strongly reinforces the mass transport of the Stream. In their analysis they report that the eddies alter the mean flow by fluxing momentum up-gradient. Up-gradient eddy fluxes were also diagnosed by *Eden et al.* [2007], where they find the eddies to contribute to the building, rather than release, of available potential energy over much of the free-jet region of the Gulf Stream. Further research on subgrid-scale parameterizations and numerical schemes is required if such up-gradient turbulent fluxes are to be accounted for at coarser resolution.

This understanding of the dominance of bottom pressure torque in generating the northern recirculation, and of the role of eddies in establishing the bottom pressure field, is reinforced in the closely related paper of *Greatbatch and Zhai* [2006]. In this later work the authors allow the mean circulation to be unconstrained while assimilating eddies from the study of *Zhai et al.* [2004], finding that the assimilated eddies contribute more weakly towards the establishment of a northern recirculation when the hydrography is allowed to drift. They also find support for the assertion of *Hogg and Stommel* [1985] of constraint within continuous f/H contours, which in the case of the anticyclonic circulation of the Northwest Corner are limited by the depth of the Gibbs Fracture Zone.

6.3. Northern limit of the Subtropical Gyre

It has already been mentioned that the North Atlantic Current's penetration into the region of the Northwest Corner represents the most poleward penetration of any of the subtropical gyres, and that this has been an even more elusive feature in models than the more widely recognized problem of Gulf Stream separation. The penetration of the NAC into the Northwest Corner would also appear to be an historically variable feature: There is evidence that the Current instead followed an eastward drift at the time of the Last Glacial Maximum, as surmised from ocean bottom sediment cores by *Robinson et al.* [1995]. *Rossby* [2003] has presented a possible mechanism for the rapid switching of the Current from LGM conditions to modern involving topographic Rossby waves.

As has also been mentioned above, ocean models used in climate general circulation models fail to produce North Atlantic Current penetration into the Northwest Corner, producing instead a gyre boundary more like that of the Northwest Pacific, or of the Northwest Atlantic at the time of the LGM. The question of whether these large biases in sea surface temperature matter to atmospheric model circulation was explored by *Weese and Bryan* [2006], where the authors used the method of *Eden et al.* [2004] (which also provided *Zhai et al.* [2004] the basis for their variant of that method) to adiabatically correct the ocean model circulation in the Northwest Atlantic, finding that correction of the sea surface temperature errors resulted in an improvement in the Icelandic Low of the atmospheric model.

It is quite unknown, however, the degree to which the path of the North Atlantic Current matters to the stability of climate in the 21st century, a line of questioning raised by *Hecht et al.* [2006]. Eddy-resolving ocean models will soon provide us with estimates of the stability of Atlantic

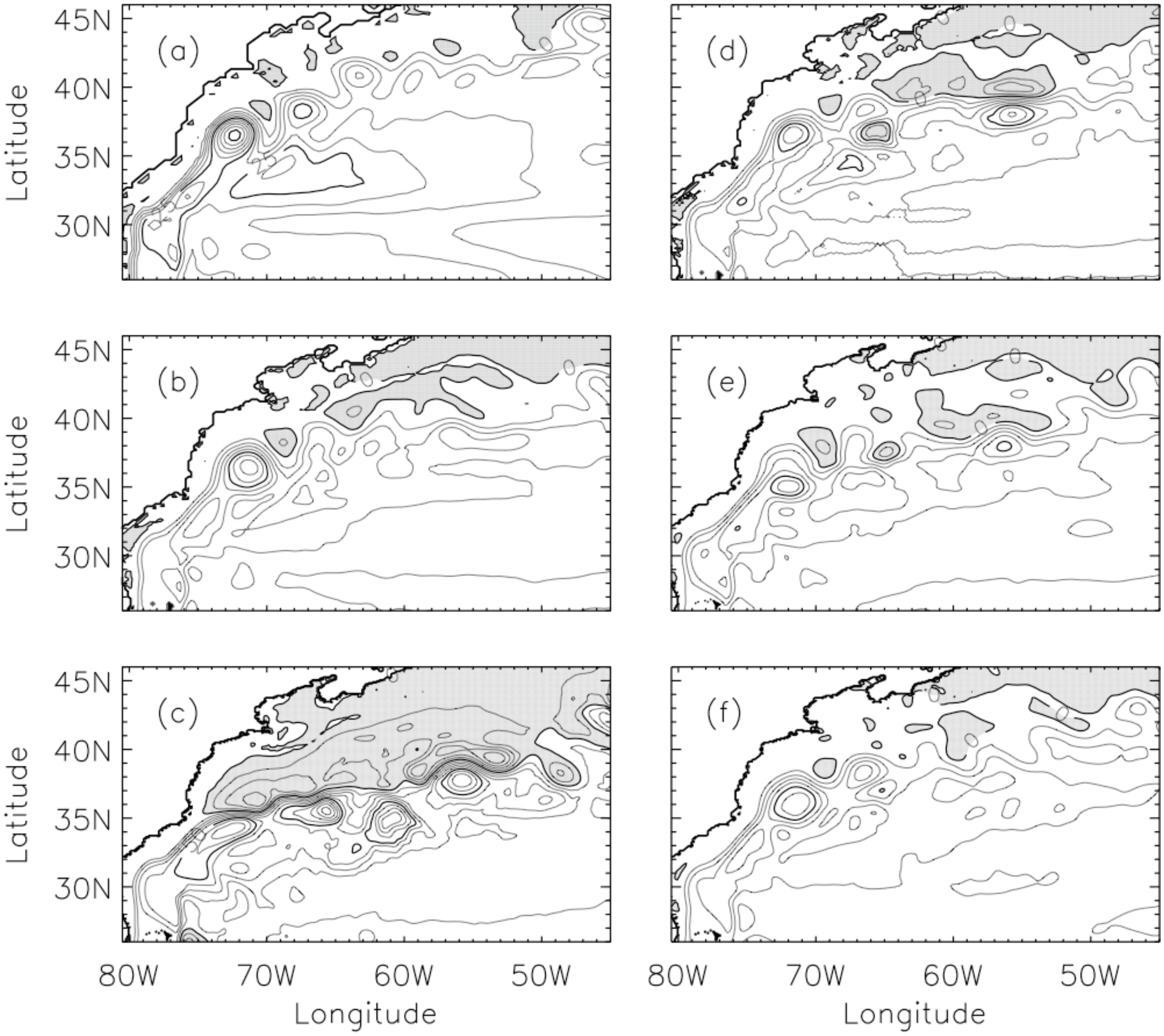


Figure 5. Barotropic stream function averaged over the period 1989–1991. Contour interval is 10 Sv (5 Sv in panel (a)), negative values are shaded. Panel (c) is from the 0.1° North Atlantic modeling study of *Smith et al.* [2000], whereas panels (b) and (a) are coarsened 0.2° and 0.4° configurations of the model, with lateral dissipation scaled as grid cell area to the 3/2 power (see *Hecht et al.* [2008], in this same volume, for a discussion of scaling of dissipation with grid cell area). Panel (d) is the 0.2° but with the lower values of lateral dissipation used in (c); panel (e) is the compliment of this, the 0.1° model but with the higher values of lateral dissipation used in (b). Panel (f) is as per (e), but with the coarser 0.2° resolution of bathymetry even though the model is otherwise configured at 0.1°. Notice that the Gulf Stream only separates at Cape Hatteras, as observed, in panel (c), with the highest resolution of 0.1° and with appropriately low value of viscosity. This figure reprinted from *Bryan et al.* [2007] (their Figure 4).

northward heat transport based on a circulation which more correctly represents the modern penetration of subtropical gyre waters into the Northwest Corner. A component of the water masses that eventually participate in deep water formation are conditioned along this Gulf Stream/North Atlantic Current path. Eddy-resolving ocean models will make a significant contribution to climate science by settling this question of the degree to which our estimates of 21^{st} century climate stability are compromised, or not, by this bias of non-eddy-resolving ocean models.

6.4. Resolution-Dependence of Northward Transports

Tremendous interest has been shown towards the estimation of Atlantic meridional overturning circulation and heat transport in recent years, as seen in the concerted effort of the Rapid Climate Change Programme of the UK's National Environment Research Council, and yet there is much still to be learned about the resolution dependence of these transports in models, as alluded to just above.

A preliminary analysis of the resolution dependence of northward heat transport in the Atlantic was presented by *Bryan and Smith* [1998]. Extending on the work of *Böning et al.* [1995], *Böning and Bryan* [1996] and *Fanning and Weaver* [1997], *Bryan and Smith* [1998] analyzed transports at resolutions of 4/10°, 2/10° and 1/10° with consistent model configuration across this range of resolution. They found a maximum in northward heat transport somewhere between 25° and 30°N in all cases. That maximum value increased by 50% from lowest to highest resolution, as shown in Figure 6, with the heat transport in the highest resolution case falling near the central value of the observational estimate of *Macdonald and Wunsch* [1996]. Nearly all of the increase in the total transport was accounted for by changes

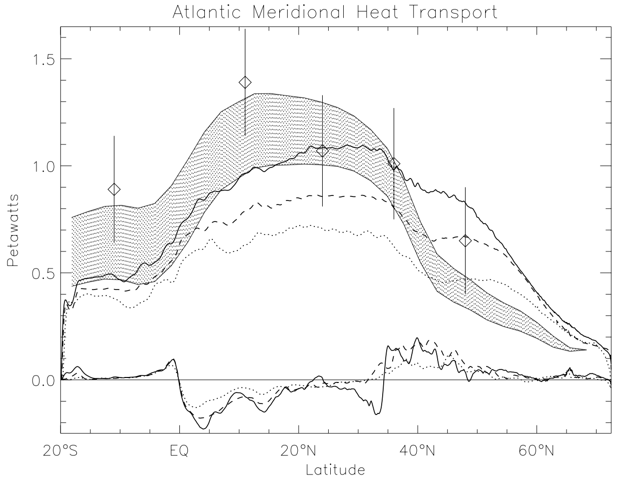


Figure 6. Net meridional heat transport (upper curves) and transport by the time varying flow (lower curves) for North Atlantic models at resolutions of 0.1° (solid), 0.2° (dashed) and 0.4° (dotted). The estimate of *Trenberth* [1998] is indicated by the shaded region and the inverse model results of *Macdonald and Wunsch* [1996] are indicated by the diamond symbols and vertical bars. Figure reprinted from *Bryan and Smith* [1998].

in the time mean flow rather than by direct contribution from eddies.

One paper that explains a role for model resolution in the variability of the meridional overturning circulation is that of *Getzlaff et al.* [2005]. Building on earlier observational and more idealized modeling work, they confirm the correlation of meridional overturning circulation (MOC) with the North Atlantic Oscillation (NAO), with the forcing leading by two to three years, and then go on to identify a rapid speed of dynamical signal propagation in an eddy-admitting (1/3°) version of their model, with the MOC response to changes in Labrador Sea deep water communicated to lower latitudes through this rapid communication.

The fast dynamical signals they see are in the form of Kelvin waves, triggered by the NAO-driven anomalies in the thickness of Labrador Sea Waters. The Kelvin waves propagate along the western boundary to the equator, where they cross the basin in the equatorial wave guide. In contrast, the non-eddy-resolving version of their model shows a far more significant lag in response time with latitude, with the signal propagation occurring at the much slower advective rate, illustrating the linkage between processes occurring at small spatial and fast temporal scales.

7. Deep Flow

The flow of the upper ocean, and the dependence of that flow on mesoscale variability, has been a focus of much discussion. The tremendous spatial and temporal coverage of remotely sensed altimetry only tends to bring more of our attention towards the surface. The response of the deep ocean to the mesoscale eddy variability, however, is every bit as remarkable as that of the upper ocean. Here, we briefly describe recent developments in our understanding of the structure of the deep flow of the Northwest Atlantic and then touch on the importance of the interaction between the Gulf Stream and the deep flow.

7.1. Export from the Subpolar Gyre

Tracer distributions imply that a significant fraction of the Deep Western Boundary Current emerges from the Labrador Sea and circulates around the Grand Banks (*Talley and McCartney* [1982], *Pickart and Smethie* [1998], *Smethie et al.* [2000]), passing from subpolar to subtropical gyres. In marked contrast, PALACE and SOLO floats, which have been used in an attempt to trace out this circulation, fail to follow such a path around the Grand Banks, detraining, instead, into the counter-flowing deep waters of

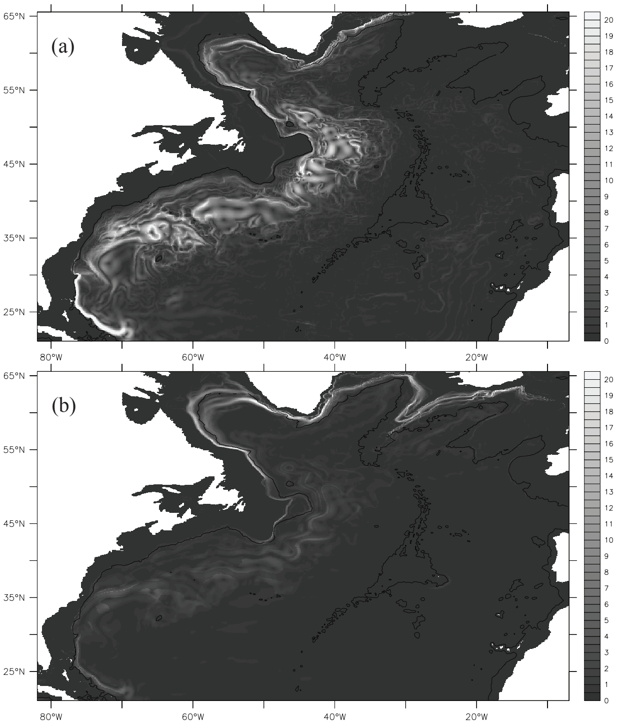


Figure 7. Deep transport within potential temperature classes, averaged over the period 1998—2000. (a) 2°—3°C class, and (b) 4°—5°C class. Units are $10^{-4} m^2/s$, such that integration over the width of any section produces the net volume transport across that section within the potential temperature class. The 2500 meter depth contour is indicated in black.

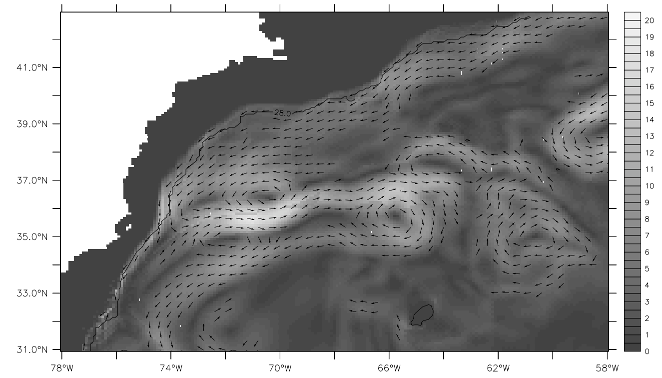


Figure 8. Deep transport, as in Figure 7, but for the 3°—4°C class over the Gulf Stream region from Cape Hatteras to the New England Seamounts. Vectors of uniform length have been added, where the transport exceeds a threshold, in order to trace out the sense of the flow.

the North Atlantic Current (*Lavender et al.* [2000], *Fischer and Schott* [2002]).

This contradiction is addressed in *Getzlaff et al.* [2006]. They work with an off-line transport model based on the flow field from a 1/12° mercator grid z-coordinate model with the bottom boundary layer scheme of *Beckmann and Döscher* [1997] (as documented in *Dengg et al.* [1999]; this is largely the same model as used in the analysis of *Eden et al.* [2007], discussed above).

The picture *Getzlaff et al.* [2006] find is consistent with the tracer observations. Of the fraction of numerical floats that make it from a release point of 53°N to the western boundary at 32°N, south of Cape Hatteras (around one in six floats), they find that 60% round the Grand Banks, with the remainder diverted through a more circuitous path, flowing eastward to the mid-Atlantic Ridge before resuming a southward course (this interior path is consistent with the tracer-based observations presented in *Rhein et al.* [2002]). The interior flow follows the Ridge until around 38°N, where it takes a largely westward course to the point where it rejoins the western boundary flow. That point where the two principal paths rejoin was found to lie in the vicinity of the crossover point, near Cape Hatteras.

The initial deflection of a sizable fraction of the DWBC is reported by *Getzlaff et al.* [2006] to occur as these waters interact with the quasi-stationary meanders of the NAC. The strength of these meanders, in turn, can be expected to depend sensitively on the the ability of a model to reproduce a strong North Atlantic Current with sufficient depth penetration, as touched on in *Bryan et al.* [2007]. The existence of this detour through which much of the flow of the DWBC passes would appear to owe its existence, therefore, to the presence of eddies.

The explanation for the failure of floats embedded in the DWBC to trace out the main branch of the Current emerges when *Getzlaff et al.* [2006] transport numerical floats that are made to surface at 10 day intervals, spending 12 hours at the surface, as for SOLO floats. As with the real-world floats, they find that few of their numerical floats follow the main branch of the DWBC around the Grand Banks. The disturbance associated with remaining in surface waters for 12 hours is simply too great; an alternative strategy involving surfacing for 2 hour periods, which is expected to be technically feasible, was found to compromise the float trajectories to a much more tolerable extent.

In the North Atlantic model of *Smith and Gent* [2004], which uses anisotropic forms of horizontal viscosity and isopycnal mixing, there is some evidence for a splitting of the deep transport into western boundary and interior branches at the Grand Banks, but with a great deal of recirculation seen in between the two branches, as shown in Figure 7 (their case A′). These deep recirculations are associated with the intensification of the Gulf Stream transport downstream of Cape Hatteras; the dominance of the mesoscale is seen even in the time-average view of Figure 7. It is also evident from the figure that waters in the denser and colder 2°—3°C class of potential temperature have their origin in the overflow of the Denmark Strait (upper panel), whereas the warmer 4°—5°C class (generally higher in the column) traces out waters from the Iceland-Faroe-Scotland Ridge.

As explained in *Smith and Gent* [2004], anisotropic forms of dissipation are particularly effective in maintaining the density of overflow waters from the Denmark Strait. The subject of entrainment within the early and intense mixing of the overflow, and the role of model formulation and resolution, is an important one which is treated in the paper of *Legg et al.* [2008], within this same volume.

7.2. Crossover

A significant fraction of the deep flow crosses under the Gulf Stream at Cape Hatteras within the Deep Western Boundary Current. *Tansley and Marshall* [2000] argue that crossover occurs here due to the steepening of topography associated with the Cape. *Bryan et al.* [2007] find evidence that the underlying deep current serves to isolate the Stream from bathymetry, such that the potential vorticity change associated with vertical stretching of cross-slope flow might be lessened.

The importance of the Deep Western Boundary Current, and the fact that steepening of the continental shelf brings the Deep Current beneath the Stream at Cape Hatteras, had been explored by *Thompson and Schmitz* [1989]. They never saw separation at Cape Hatteras in their two layer, 0.2° model, but saw southward migration of the offshore Stream (after late separation). Now, with the benefit of more recent findings from models combining realistic configuration and a more realistic mesoscale eddy spectrum (*Bryan et al.* [2007]), it appears that the argument of *Tansley and Marshall* [2000] that the point of separation is locally fixed through topographic constraint is correct. Furthermore, findings to date, as surveyed above, strongly suggest that a realistically intense interaction between the Stream and Deep Western Boundary Current is required for separation to occur in a model; this requirement for a realistically strong Deep Western Boundary Current in turn requires eddy-mediated processes of energy conversion to invigorate the deep flow.

A point that is not widely appreciated is the effect of the interaction between the two currents on the deep flow at the crossover, where much of the deep flow is swept along with the Stream to the east. This is particularly clear in the 3°—4°C potential temperature class, shown in Figure 8, where the eastward excursion of the deep flow is only turned back at the New England Seamount Chain. A strong, well defined Deep Western Boundary Current is reestablished shortly before reaching The Bahamas (see Figure 14 of *Smith et al.* [2000] for a model section of velocity off Abaco).

This split of the deep western boundary current, with the upper layers being carried to the east along with the Gulf Stream, was identified from hydrographic survey data in *Pickart and Smethie* [1993], and later confirmed with the Lagrangian float study of *Bower and Hunt* [2000]. The split was first studied within a model by *Spall* [1996a], and the implications for eddy-mean flow influence on the southern recirculation gyre explored further in *Spall* [1996b], where the Gulf Stream and upper core of the deep western boundary current were seen to form a low-frequency oscillator which may present a source of decadal variability.

8. Summary

Since the last set of published reviews a dozen years ago (*Stammer and Böning* [1996], *Böning and Bryan* [1996] and *Dengg et al.* [1996]), modeling of the North Atlantic Ocean has moved from what would be called the eddy-admitting regime into the eddy-resolving regime: Eddy kinetic energies are now in much better agreement with observations. It has become clear that the variability in the circulation is generally stronger than the mean, apart from the regions occupied by mean jets.

The Gulf Stream separates at the observed location of Cape Hatteras in these eddy-resolving models, although results remain very sensitive to model configuration. Major improvements are seen downstream in the Gulf Stream system as well, with a North Atlantic Current that rounds the Grand Banks, correctly forming a remarkable poleward penetration of subtropical gyre waters into the region of the Northwest Corner. The Azores Current also branches off of the Gulf Stream in the vicinity of the Southeast Newfoundland Rise in these models, forming a front that presents an important constraint on the spreading of mode waters.

It is not entirely clear, at this point, where increased resolution is working to better resolve eddies and where the greater impact of resolution may perhaps lie in finer resolution of the topography, though *Bryan et al.* [2007] addressed this question in a limited sense. There is evidence supporting the use of even higher resolutions in order to adequately resolve processes within the mixed layer: the 1/20° study of *Paci et al.* [2007] provides evidence for the importance not only of the mesoscale, but of the sub-mesoscale. The relevance of the sub-mesoscale is discussed further in *Thomas et al.* [2008], in this same volume with our paper. Analysis of high resolution simulations will contribute to further development of parameterizations, particularly in terms restratification of the mixed layer, as in *Fox-Kemper et al.* [2007].

An issue which has only been lightly addressed is that of appropriate forcing for strongly eddying ocean models. The mismatch between high resolution ocean and low resolution reanalysis is one that has been discussed informally for years. Performing initial fully coupled simulations with high resolution ocean and relatively low resolution atmosphere is attractive, as a means to minimize the number of variables changed and perhaps maximize understanding, but the extent to which this may compromise the effect of air-sea fluxes remains to be determined.

Further progress on all of these issues could of course be enhanced by the continued development and adoption of metrics. This is a developing area where strongly eddying simulations figure prominently because of their more satisfactory comparison with observations (see *McClean et al.* [2002], *McClean et al.* [2006] and *McClean et al.* [2008]).

Even acknowledging gaps in our understanding, it does appear that improvements in the deep circulation are as meaningful as those seen in the upper ocean. Repeatedly through the years comment has been made on the invigoration of the deep flow with the inclusion of eddies, as eddy mediation of energy conversion between baroclinic and barotropic modes works to couple the circulation of the upper ocean to that of the depths, and to bring the influence of topographic torque on the large scale circulation to a more realistic level. It appears that this eddy-mediated coupling of circulations in the deep and upper ocean is fundamental to the establishment of the Northern Recirculation Gyre, and to the North Atlantic Current's northward excursion around the Grand Banks.

Density differences are small enough in the Northwest Atlantic that much of the steering must be produced by topographic torque, as pointed out by *Treguier et al.* [2005]. In turn then topography presents a major constraint on layer thickeness — on the potential vorticity of the flow — and hence eddies and topography together play a major role in determining the large scale dynamics of the North Atlantic.

This coupling of upper ocean and depths also appears to be critical to the determination of the degree to which the Deep Western Boundary Current and Gulf Stream interact at Cape Hatteras. At this location, the steep topography of the shelf at Cape Hatteras causes the two currents to cross, with sufficient strength of interaction required in order for the separation to occur, along with a sufficiently inertial character of the Stream. This is how we best understand the process of Gulf Stream separation in our most realistic, eddy-resolving models today.

The North Atlantic has also provided a context for theoretical development, most notably with respect to the effects of eddies and the parameterization of those effects in lower resolution models. Even while our ability to parameterize the effect of eddies is developing, however, we are presented now with the possibility to re-evaluate the stability of Atlantic meridional overturning circulation, and the stability of 21^{st} century climate, with models that produce a very much more realistic path of the North Atlantic Current, and hence corrected preconditioning of those waters that subsequently participate in the formation of North Atlantic Deep Water.

When the first coupled climate simulations of 21^{st} century climate are performed, initialized with the more realistic mean ocean circulation which may be attained with a strongly eddying ocean, the question of whether the stability of the meridional overturning is different than in today's models will be one of the important questions to be posed. If the stability of the overturning is found to be substantially different than with non-eddying models, then we anticipate that further numerical experimentation will be required in order to understand the robustness of the results with confidence.

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