John von Neumann Institute for Computing

Sensitivity Studies with Numerical Models of Medium Resolution of the Atlantic Ocean

Jens-Olaf Beismann, René Redler

published in

NIC Symposium 2001, Proceedings,
Horst Rollnik, Dietrich Wolf (Editor),
John von Neumann Institute for Computing, Jülich,
NIC Series, Vol. **9**, ISBN 3-00-009055-X, pp. 443-452, 2002.

http://www.fz-juelich.de/nic-series/volume9

Sensitivity Studies with Numerical Models of Medium Resolution of the Atlantic Ocean

Jens-Olaf Beismann[1] **and René Redler**[2]

[1] Institut für Meereskunde, Universität Kiel
Düsternbrooker Weg 20, 24105 Kiel, Germany
E-mail: jobeismann@ifm.uni-kiel.de

[2] C&C Research Laboratories, NEC Europe Ltd.
Rathausallee 10, 53757 Sankt Augustin, Germany
(previously at GMD SCAI, Schloss Birlinghoven Sankt Augustin)
E-mail: rene.redler@ccrl-nece.de

The numerical simulation of the uptake and redistribution of chlorofluorocarbons (CFC) provides a powerful tool for studying the mechanisms of water mass formation and spreading in ocean circulation models. Uptake of atmospheric trace gases of which CO_2 is another prominent example is strongly influenced by oceanic physical variability at spatial scales below 100 km. A realistic representation of this uptake in numerical models is essential for future climate studies.

In the present study we use dissolved CFCs as a tracer to analyze the renewal of North Atlantic Deep Water and its pathways in different prognostic 3-d models of the Atlantic. Results of several long-term model integrations are presented to discuss the physical processes determining the temporal evolution of the 3-d CFC distribution in the deep ocean. Effects of different subgrid scale parameterizations are discussed. In particular we address the southward transport of CFC-enriched water with the Deep Western Boundary Current.

1 Introduction

The North Atlantic Deep Water (NADW) with its source water masses is a major component of the global oceanic thermohaline circulation. Understanding the formation processes of the different water mass components of NADW and the uptake of anthropogenic trace gases going along with this is still a key issue when investigating the global circulation, the coupled ocean-atmosphere climate system and the ocean in particular as one of the major sinks for anthropogenic CO_2. As often pointed out in the literature such processes take place on a relatively small scale compared to the basin wide circulation. Formation rates of NADW turn out to be highly variable in time from interdecadal timescales down to days. Prominent examples of these are the interdecadal variability of Labrador Sea convection, the Denmark Strait Overflow or the Iceland Faroer Overflow.

Due to the sparse coverage in both space and time of field measurements the question of how these processes are related to the climate system and how they interact with each other cannot be answered from observations alone. Numerical models are valuable and widely accepted tools to gain deeper understanding and insight into the natural phenomena. To simulate the global circulation with a certain degree of realism, sufficiently high resolution in both space and time is required.

Tracing the uptake and redistribution of chlorofluorocarbons (CFC) provides a powerful tool to study the ocean circulation and the mechanisms of water mass formation, both in the real ocean and in numerical simulations[1,2]. With respect to model results the intercomparison of field measurements and modeled CFC distributions serves as a useful means for assessing the models capability of detecting and describing processes in key regions of water mass formation and their propagation in current regimes like the Deep Western Boundary Current (DWBC). In combination with observed CFC distributions these tracers thus help to determine whether a model correctly simulates NADW formation rates, pathways and mean current speeds[3].

CFCs have frequently been used for this purpose (cf. the recent review by England and Maier-Reimer[4]), mostly with models of rather coarse horizontal resolution of about 2° to 4° in latitude and longitude. In comparing results of these models with observations the question arises which aspects of the model solutions can be assumed to be fairly independent of the model resolution and/or model configuration, and which features are likely to change with future generations of models of higher resolution.

Another issue of very coarse resolution models addresses the high diffusivity and its impact on the water mass propagation and distribution. Ideally, the sub-grid scale parameterization employed by any numerical model should not affect the propagation rate of a signal when compared with higher resolution models and observations.

A series of systematic studies on the impact of various mixing schemes has already been published by England and Hirst[5] and England and Holloway[3]. While all the numerical experiments presented in these studies show reasonable production rates and southward transports of NADW, this must go along with low velocities at individual grid points located in the DWBC region: The DWBC as a narrow current along the continental shelf is hardly resolved with coarse resolution models, and individual velocities represent an average over the whole volume of the respective grid box which has to represent both a core of the very fast DWBC and weak currents further offshore. One of the logical consequences is an underestimation of ventilation rates of water masses directly influenced by NADW.

Uptake of CO_2 (another prominent anthropogenic trace gas) by the ocean is a key issue for understanding and predicting the behavior of the climate system. In contrast to CO_2, CFCs are easier to include in numerical models because of their chemical inertness and their well known timeseries of nearly homogeneous atmospheric concentrations over the last decades. Detailed knowledge about how the representation of gas uptake affects calculated inventories are crucial for a correct interpretation of scenarios addressing the uptake e.g. of anthropogenic CO_2. Previous authors[6,4] have explored the sensitivity of the simulated air-sea gas fluxes to parameterizations of the gas transfer velocity, but since they restricted themselves mainly to the comparison of tracer concentrations on certain ocean sections, very little can be found in the literature concerning the influence of gas flux parameterizations on oceanic inventories of dissolved trace gases. Furthermore the numerical models used in the above mentioned studies were of rather coarse resolution (typically of the order of 4°), leading to large uncertainties in the representation of key processes governing the trace gas uptake like e.g. convection in the Labrador Sea. It is thus possible that these earlier findings might change when models with finer grid spacing are employed.

In section 2 we introduce the technical details of the numerical model we employed, and we present some results of our experiments in section 3.

2 Experimental Design

The FLAME (*Family of Linked Atlantic Model Experiments* [a]) code we use for our model studies is based on the Modular Ocean Model (MOM[7]) from the Geophysical Fluid Dynamics Laboratory in Princeton.

Technical details addressing the model configuration and parallelization strategy have already been published at the beginning of this project[8]. For further details the reader is kindly referred to this document accessible via
`http://www.rzg.mpg.de/mpp-workshop/proceedings.html`.

2.1 Physical Setup

Since the physical processes under consideration are mainly restricted to the Atlantic and not much influenced by the rest of the world ocean we limit ourselves to model the Atlantic only. Our model (Figure 1) area covers the region of the Atlantic Ocean and is situated between 70°N and 70°S with open boundaries across the Antarctic Circumpolar Current in the Drake Passage (70°W) and south of Africa at 30°E following the approach of Stevens[9]. The northern and southern boundaries are closed. To include the effect of water mass formation in the Greenland Sea a restoring area taken from the DYNAMO experiments[10] is used for all our case studies.

The horizontal resolution of the locally rectangular grid is 4/3° in longitude and 4/3°$\times \cos(\phi)$ in latitude (ϕ) resulting in a mesh size of 148 km at the Equator decreasing to 50 km at the subpolar boundaries. The vertical is discretized in 45 levels, with a spacing of 10 m in the uppermost level and a smooth increase to 250 m at 2500 m depth. Below 2500 m the vertical grid box thickness is a constant 250 m up to a maximum depth of 5500 m.

MOM is a Fortran code based on the so called "primitive equations"[11] which are derived from the Reynolds-averaged Navier-Stokes equations under various assumptions, like the Boussinesq, spherical and hydrostatic approximation. From these equations MOM calculates prognostic values of the horizontal velocity, potential temperature (Θ) and salinity (S) distribution. Density and pressure are constructed from the Θ and S fields. In addition to that, we calculate the distribution of two species of chlorofluorocarbons (CFC-11 and CFC-12) as supplementary tracers. The equations are discretized on a regular three-dimensional grid with depth as vertical coordinate.

For solving the momentum equations, the horizontal velocities are split up into a vertical average and its deviations. The vertically averaged transport can be expressed by a 2-dimensional stream function which is described by a Poisson equation. The latter is solved using an iterative conjugate gradient method. Additional constraints are needed to keep the values around the islands constant during every iteration step.

Due to the hydrostatic approximation the vertical component of the momentum equation degenerates, and the vertical transport due to hydrostatic instabilities (convection) has to be parameterized. Vertical velocities are diagnoseed from the divergent horizontal velocity field.

The remaining 2^{nd} order non-linear partial differential equations for Θ, S and the vertical shear of horizontal momentum are solved on regular 3-D grids using the finite vol-

[a] `http://www.ifm.uni-kiel.de/fb/fb1/tm/research/FLAME/index.html`

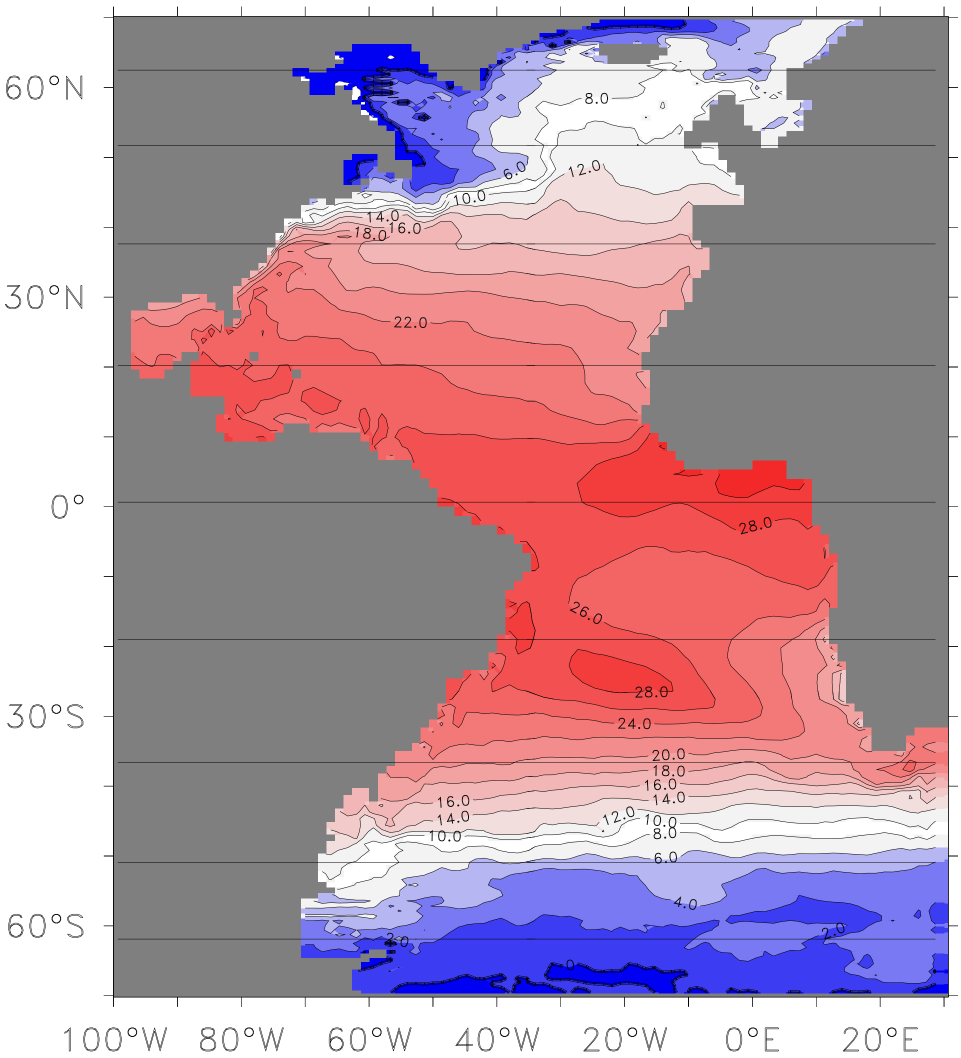

Figure 1. Sea surface temperature as simulated by the FLAME 4/3° Atlantic model. Horizontal lines indicate the data partitioning. By applying 10 PEs each processor has to work on 15 rows. Unequal spacing between horizontal lines are due to the map projection used.

ume/difference approach. Explicit time stepping is used. Central differences are applied in space. Time discretization is done with central differences (so called "leap-frog" scheme) as well but replaced at regular intervals by a backward Euler time step in order to damp the computational mode.

For horizontal diffusion of tracers, e.g. Θ, S and CFCs we use mixing along isopycnal surfaces[12, 13]. This implicit approach requires the inversion of a tridiagonal matrix accompanied by a rotation of the mixing tensor into the direction of surfaces of constant density. Some experiments employ the eddy induced tracer advection parameterization according to Gent and McWilliams[14], in some cases with horizontal background diffusion. Both coefficients, isopycnal diffusivity and thickness diffusivity for the Gent&McWilliams parameterization (GM90, hereafter), are set to $2 \cdot 10^7$ cm^2/s decaying with depth to $0.5 \cdot 10^7$ cm^2/s below 4000 m. Along boundaries the coefficients are kept zero. Constant coefficients are chosen for horizontal viscosity of $10^8 \cdot \cos\phi$ cm^2/s.

Simulating the oceanic uptake and spreading of anthropogenic tracers requires an appropriate representation of the flow of dense water masses across shallow sills which in our model is achieved by a bottom boundary layer parameterization according to Beckmann and Döscher[15].

The atmospheric climatological forcing applied to our experiments is based on a 3-year monthly mean climatology of ECMWF (European Center for Medium Range Weather Forecast) analysis (1986 to 1988)[16], and relaxation to surface salinity given by Boyer and Levitus[17]. The thermal boundary condition is described by Barnier et al.[16] and uses linearized bulk formulas to define a model dependent air-sea net heat flux as a relaxation to an equivalent sea surface temperature. The wind stress is also derived from the same ECMWF analysis[18].

The ECMWF wind stresses, atmospheric equilibrium temperature, friction velocity and sea surface salinity fields were all converted to pseudo fields as proposed by Killworth[19], in order to achieve correct monthly means. For several experiments we use monthly mean heat flux and wind stress anomalies (with respect to a long term mean) taken from the NCEP/NCAR reanalysis for years 1958 to 1996[20] which had been added to our climatology[21].

All individual experiments are initialized with January Θ and S fields and are spun up from a state of rest for an integration period of 20 model years followed by an analysis phase of 47 years to hindcast the time span from 1950 to 1996.

2.2 Computational Requirements

Our model domain encompasses 533250 grid points. With 7 prognostic variables to calculate and a time step of 1 hour (8760 time steps per model year) we need about 37.5 hours CPU time to simulate 1 model year on a Cray T3E-1200. Running the executable on 15 PEs, this accounts for roughly 2.5 hours elapsed time and a total of 165 hours elapsed time is required to complete a single experiment for a full 66 year period. These requirements allow us to perform the sensitivity studies described above by exploring various parameterizations of subgrid scale physics.

The disk requirements for this model are moderate: For each individual job (1 year simulation) the diagnostic output sums up to 1.5 Gbyte which is reduced to 300 Mbyte in a separate postprocessing phase. For each individual experiment the total amount of data for a full 67 year integration to be stored permanently for further analysis sums up to approximately 20 Gbyte.

It is tempting to compare results of the configurations described so far with a model of somewhat higher resolution in space and time which is able to resolve the sub-grid scale physics explicitly to a wider extent.

The numerical model we designed for this purpose ($1/3^\circ \times 1/3^\circ \cos(\phi)$ horizontal resolution) encompasses 8.3 million grid points. Using a time step of 20 minutes (25920 time steps per model year) the required CPU time to perform 1 year of simulation sums up to 1080 hours which (running the executable on 120 PEs on a T3E-1200) results in an elapsed time of 9 hours. Due to limitations of the queue system the jobs had to be split up into 3 spanning the time frame of 4 months each. The temporary disk space required for the output of each individual job then adds up to 4.2 Gbyte. For each model year 3.9 Gbyte of pre-analyzed data have to be stored permanently for later analysis. Furthermore a permanent disk space of 1 Gbyte is required to provide the necessary input data to the model.

Due to limitations in CPU time and disk space, performing a high resolution run comparable to the experimental setup described above would have taken 1 year real time on the given system and environment without allowing us to perform any further sensitivity studies beside this one to compare with during this time[b].

3 Simulation Results

Basin scale numerical ocean models do not resolve mesoscale eddies due to their coarse resolution. Instead they have to rely on some parameterization to represent the mixing effect of eddies on tracer distributions.

Here we will discuss briefly the CFC-12 distribution in the upper part of NADW (uNADW) from a series of experiments (B1.7, B1.9 and B1.N4) that have been conducted on the CRAY-T3E. In our 4/3° configuration different mixing parameterizations have been employed. For the qualitative comparison of tracer distributions we use CFC-12 concentrations on an isopycnal surface (surface of constant density) corresponding to the tracer maximum in the uNADW, usually ρ_0 = 1027.78 kg/m^3. ρ_0 is the density of sea water for a given temperature and salt content referenced to the sea surface.

Numerical models at this resolution suffer from unrealistic uNADW propagation pathways marked by the CFC signal when simple mixing parameterizations are used. In general the simulated CFC distribution is much too diffusive compared to field observations, leading e.g. to a broad DWBC instead of a narrow and concentrated boundary current. In addition, the CFC signal in the eastern parts of the subtropical and subpolar Atlantic reaches too far to the south (Figure 2, upper right panel).

The introduction of the GM90 parameterization of eddy-induced tracer advection improves our simulation in some aspects (Figure 2, upper left panel): The eastward outflow from the Labrador Sea is reduced, leading to a less intense CFC propagation in the eastern basin of the North Atlantic. The southernmost extension of a given isoline can now clearly be found in the western basin, whereas isolines have a much more zonal direction in the experiment without GM90. At the same time, the already sluggish DWBC in experiment B1.9 has slowed down in the GM90 run (B1.7), and the associated tracer signal cannot make its way around the Grand Banks into the subtropical Atlantic. The core of the CFC-12 maximum is not connected to a boundary current structure, but propagates southward in the interior of the basin. Also, the tracer tongue does not reach as far across the equator and into the South Atlantic as in experiment B1.9. The effect of the GM90 parameterization to mimic the conversion of available potential energy to eddy kinetic energy by flattening

[b] An integration of the 1/3° (2 × 50 years) has been started 2 months ago on the SX5 at HLR Stuttgart. At the time of writing this paper the first phase of the integration was completed. Numerical results are currently under investigation.

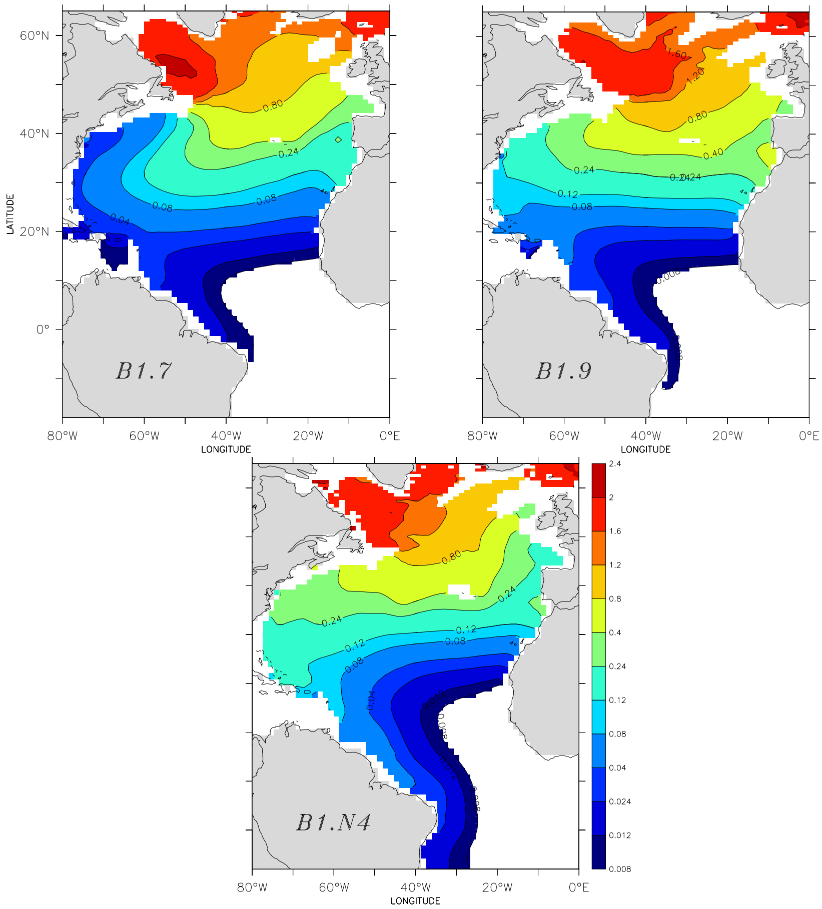

Figure 2. Distribution of CFC-12 (in pmol/l) on an isopycnal surface in the upper North Atlantic Deep Water for experiments with pure isopycnal diffusion (upper right), with isopycnal diffusion and the GM90 parameterization (upper left), and topographic stress parameterization (lower).

isopycnal surfaces and modifying the tracer advection speed has important consequences for our simulated DWBC: underneath the Gulf Stream, the slope of the isopycnal surfaces is so weak that it is not possible to reverse the flow direction with increasing depth (via thermal wind). Therefore, NADW outflowing from the subpolar North Atlantic to the south has to pass on the off-shore side of the Gulf Stream which leads to the tracer distribution described above. Tracer observations on meridional sections southwest of the Grand Banks[22,23] show that in addition to the uNADW CFC maximum on the continental shelf, local maxima of lower concentration exist in the interior. These have been attributed to recirculation cells in the DWBC, but they do not support the single interior maximum simulated in our GM90 experiment.

Holloway[24] proposed a parameterization that tries to represent the interaction of (un-resolved) mesoscale eddies with bottom topography. Based on statistical mechanics, this parameterization induces a cyclonic (counter-clockwise on the northern hemisphere) circulation along topographic slopes even if the ocean model is not forced by atmospheric fluxes of momentum or buoyancy. Our experiment B1.N4 (Figure 2, lower panel) includes this parameterization, and we can identify important differences to the simulations with the more "classic" eddy parameterizations: A Deep Western Boundary Current has been established all along the American continental shelf where the fastest tracer propagation can be found. The southward extension of the tracer tongue reaches further across the equator than in experiments B1.7 and B1.9, and the unrealistic eastward spreading in the subpolar gyre has been further reduced. While these findings underline the role of bottom topography for the deep circulation, a more quantitative assessment of experiment B1.N4 will be necessary to explore implications for the integrated tracer uptake.

4 Conclusions

A model hierarchy of the Atlantic has been used to study formation processes of NADW as one of the most prominent water massees for the global ocean circulation which can easily be detected due to its high content of CFC. To complement previous studies of this kind performed with models of rather coarse resolution, we employed a model with a horizontal resolution of $4/3^\circ \times 4/3^\circ \cos(\phi)$ encompassing the Atlantic in the latitudinal range 70°N to 70°S. Sensitivity studies with respect to various mixing parameterizations are investigated.

Although not addressed in the very details in this paper, a first comparison with observed CFC data showed that our model is well able to capture features like the surface concentration, ventilation of intermediate layers in the subpolar North Atlantic and the formation of the DWBC. Nevertheless when looking at important details of the simulation it turns out that e.g. the velocities in the DWBC are to weak in models of this resolution and the CFC signal in general is far too diffusive. From this point of view higher resolution is necessary in order to achieve realistic simulations.

This may have important implications for modeling studies of the ocean's role in the global carbon cycle and for climate change scenarios which, because of the long integration periods have to rely on very coarse grid ocean models. The modeled global circulation pattern as well as renewal rates of water masses in the deep ocean basins may be subject to changes once the hardware is available to apply models of higher resolution in long time integrations for climate scenarios.

Acknowledgments

The authors gratefully acknowledge the work of Klaus Ketelsen, SGI Munich for his work on optimizing the code for the T3E. The work of the FLAME group is acknowledged for its contribution at various stages of the project. Model results have been analyzed using the Ferret plotting package, kindly provided by Steve Hankin and his team from NOAA/PMEL. The sensitivity studies have been carried on the Cray T3E-1200 at the John-von-Neumann Computing Center Jülich, while one of the authors (RR) was working at the GMD (now Fraunhofer) Institute for Algorithms and Scientific Computing, Sankt Augustin, Germany.

References

1. M. Rhein. The Deep Western Boundary Current: tracers and velocities. *Deep–Sea Res.*, 41(2):263 – 281, 1994.
2. M. H. England. Using chlorofluorocarbons to assess ocean climate models. *Geophys. Res. Lett.*, 22:3051–3054, 1995.
3. M.H. England and G. Holloway. Simulations of cfc content and water mass age in the deep north atlantic. *J. Geophys. Res.*, 103(C8):15885 – 15901, 1998.
4. M.H. England and E. Maier-Reimer. Using chemical tracers to assess ocean models. *Rev. Geophys.*, 39:29–70, 2001.
5. M. H. England and A. C. Hirst. Chlorofluorocarbon uptake in a world ocean model. 2. Sensitivity to surface thermohaline forcing and subsurface mixing parameterizations. *J. Geophys. Res.*, 102:15709–15731, 1997.
6. M. H. England, V. Garcon, and J.-F. Minster. Chlorofluorocarbon uptake in a world ocean model. 1. Sensitivity to the surface gas forcing. *J. Geophys. Res.*, 99:25215–25233, 1994.
7. R. C. Pacanowski. MOM 2 Documentation, User's Guide and Reference Manual. Technical Report 3, GFDL Ocean Group, 1995.
8. R. Redler, K. Ketelsen, J. Dengg, and C.W. Böning. A high-resolution numerical model for the circulation of the Atlantic ocean. In H. Lederer and Friedrich Hertweck, editors, *Proceedings of the Fourth European SGI/CRAY MPP Workshop*, pages 95 – 108. Max-Planck-Institut für Plasmaphysik, 1998.
9. D. P. Stevens. The open boundary condition in the United Kingdom Fine–Resolution Arctic Model. *J. Phys. Oceanogr.*, 21:1494–1499, 1991.
10. J. Willebrand, B. Barnier, C.W. Böning, C. Dieterich, P. Killworth, C. Le Provost, Y. Jia, J.-M. Molines, and A. L. New. Circulation characteristics in three eddy–permitting models of the North Atlantic. *Prog. Oceanogr.*, 48:123–161, 2001.
11. P. Müller and J. Willebrand. Equations for oceanic motions. In *Landolt–Börnstein, Group V, Oceanography, Volume 3b*, pages 1–14. J. Sündermann, Ed., Springer Verlag, Berlin, 1989.
12. M. H. Redi. Oceanic isopycnal mixing by coordinate rotation. *J. Phys. Oceanogr.*, 12:1154–1158, 1982.
13. M. D. Cox. Isopycnal diffusion in a z–coordinate model. *Ocean Modelling*, 74:1–5, 1987. unpubl. manuscr.
14. P. R. Gent and J. C. McWilliams. Isopycnal mixing in ocean circulation models. *J. Phys. Oceanogr.*, 20:150–155, 1990.
15. A. Beckmann and R. Döscher. A method for improved representation of dense water spreading over topography in geopotential–coordinate models. *J. Phys. Oceanogr.*, 27:581–591, 1997.
16. B. Barnier, L. Siefridt, and P. Marchesiello. Thermal forcing for a global ocean circulation model using a three–year climatology of ECMWF analyses. *J. Mar. Systems*, 6:363–380, 1995.
17. T. P. Boyer and S. Levitus. Objective analyses of temperature and salinity for the world ocean on a 1/4 degree grid. Technical report, NOAA Atlas NESDIS 11, U.S. Gov. Printing Office, Washington, D.C., 1997.
18. L. Siefridt. *Validation des données ERS-1 et des flux de surface du CEPMMT dans le*

contexte de la modélisation des circulations océaniques á l'échelle d'un bassin. PhD thesis, Université Joseph Fourier - Grenoble I, 1994.
19. P. D. Killworth. Time interpolation of forcing fields in ocean models. *J. Phys. Oceanogr.*, 26:136–143, 1996.
20. E. Kalnay, E. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph. The ncep/ncar 40-years reanalysis project. *Bull. Amer. Meteor. Soc.*, 77:437–471, 1996.
21. C. Eden and J. Willebrand. Mechanism of interannual to decadal variability of the north atlantic circulation. *J. Clim.*, 14:2266–2280, 2001.
22. W.M. Smethie, Jr. Tracing the thermohaline circulation in the western north atlantic using chlorofluorocarbons. *Prog. Oceanogr.*, 31:51–99, 1993.
23. W.M. Smethie, Jr. Meridional distribution of cfcs in the western subtropical atlantic ocean. *International WOCE newsletter*, 37:15–17, 1999.
24. G. Holloway. Representing topographic stress for large-scale ocean models. *J. Phys. Oceanogr.*, 22:1033–1046, 1992.