Impact of an adiabatic correction technique on the simulation of CFC-12 in a model of the North Atlantic Ocean

Jun Zhao[1], Richard J. Greatbatch[1], Jinyu Sheng[1], Carsten Eden[2] and Kumiko Azetsu-Scott[3]

[1]Department of Oceanography, Dalhousie University, Halifax, NS, Canada, B3H 4J1
[2]Ifm-GEOMAR, Kiel, Germany
[3]Bedford Institute of Oceanography, Dartmouth, NS, Canada, B2Y 4A2

Abstract.
A model of the North Atlantic Ocean is used to simulate the spreading of CFC-12 from the Labrador Sea deep convection site. The standard version of the model fails to capture the local maximum in CFC-12 concentration that is observed along the continental slope of the western boundary. Hydrographic data are used to apply a simple correction to the model's horizontal momentum equations. The corrected model is much more successful at capturing the nearslope maximum in CFC-12 concentration than the uncorrected model and also exhibits a 50% increase of the deep southward export of CFC-12 at 24^oN. The difference between the two model runs is shown to be a consequence of the different paths taken by the Deep Western Boundary Current in the two model versions.

1. Introduction

The semi-prognostic method (SPM) was introduced by *Sheng et al.* [2001] as a simple means of adjusting an ocean model to correct for systematic model error (e.g. poor representation of the Gulf Stream and the North Atlantic Current systems, see *Eden et al.* [2004]). The adjustment is achieved using hydrographic data as input, but whereas in the robust diagnostic method of *Sarmiento and Bryan* [1982] the correction is applied to the model potential temperature and salinity equations, the semi-prognostic correction is applied to the model momentum equations. Since the active tracer equations carried by the model are unchanged by the SPM (i.e. the method is adiabatic), the equations governing passive tracers are also unchanged. For this reason, the SPM is ideal for use in studies using passive tracers. In this letter we provide the first example of the use of the SPM in a tracer study.

Chlorofluorocarbons (CFCs) are anthropogenic compounds released into the atmosphere since the 1930's. CFCs enter the ocean by gas exchange at the sea surface and are then subducted into the thermocline or mixed through convection to the deep ocean. Since CFCs are chemically and biologically inert in sea water, their temporal and spatial distribution can be used to identify water mass pathways, in particular the equatorward spreading of newly formed dense water masses and their associated climate anomalies [*Fine et al.*, 2002]. It follows that a model's ability to simulate the observed distribution and spreading of CFCs provides a stringent test of a model's veracity and its suitability to study the carbon cycle, and the uptake of anthropogenic CO_2 by the ocean. *England et al.* [1994] were the first to attempt a simulation of the uptake and spreading of CFCs using a three-dimensional global ocean model. Model-calculated CFC concentrations have since been used to test model physics parameterizations (see *England and Maier-Reimer* [2001] and *Beismann and Redler* [2003] for an overview), and attempts have been made to fit observed and modelled CFC distributions by adjusting the gas exchange coefficient used in the model [*Gray and Haine*, 2001; *Haine et al.*, 2003]. *Dutay et al.* [2002] compared the simulated CFC fields produced by 13 different global ocean models, with horizontal resolutions ranging from 0.5° to 5°. They noted the difficulty models have in simulating the CFC distribution in the Deep Western Boundary Current (DWBC) region of the North Atlantic (see also *England and Holloway* [1998]). Here, we show the impact of the SPM on the simulation of CFC-12 in a model of the North Atlantic.

2. The semi-prognostic method (SPM)

A comprehensive review of the SPM is given by *Greatbatch et al.* [2004]. In the standard version (*Sheng et al.* [2001]), the density in the model's hydrostatic equation is replaced by a linear combination of model-computed (ρ_m) and climatological (ρ_c) density:

$$\frac{\partial p}{\partial z} = -g(\alpha\rho_m + (1-\alpha)\rho_c). \qquad (1)$$

Here p is the pressure variable carried by the model and $0 \le \alpha \le 1$. Putting $\alpha = 1$ ($\alpha = 0$) makes the model purely prognostic (diagnostic). p is not the same as the physical pressure, p^*. The latter satisfies the usual hydrostatic equation, $\frac{\partial p^*}{\partial z} = -g\rho_m$, and surface boundary condition, $p^* = g\rho_o\eta$, where η is the sea surface height and ρ_o is a representative density for sea water (note that $p = p^*$ at the surface; see *Greatbatch et al.* [2004]). Putting $p = p^* + \hat{p}$, and substituting for p in the model's horizontal momentum equation then gives

$$\frac{\partial \mathbf{v}}{\partial t} + ... + \mathbf{f} \times \mathbf{v} = -\frac{1}{\rho_o}\nabla p^* - \frac{1}{\rho_o}\nabla \hat{p} + ..., \qquad (2)$$

where $\mathbf{v}$ is the horizontal velocity vector and $\mathbf{f} \times \mathbf{v}$ is the Coriolis term. It is clear from (2) that use of the SPM adds

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a correction term, $-\frac{1}{\rho_o}\nabla\hat{p}$, to the model's horizontal momentum equation. Importantly, the tracer equations carried by the model are unchanged. Since the standard version of the SPM depends on the instantaneous model state, it does have some inherent drawbacks (e.g. reduced wave propagation speeds, damped mesoscale eddy activity and spurious interaction with topography). *Eden et al.* [2004] introduced modified methods to overcome these drawbacks. To see how the modified methods work, we rewrite (1) in the form

$$\frac{\partial p}{\partial z} = -g\rho_m - g(1-\alpha)(\rho_c - \rho_m) \tag{3}$$

so that $-g(1-\alpha)(\rho_c - \rho_m)$ appears as the semi-prognostic correction term. In the "smoothed" and "mean" methods, the correction term is smoothed spatially and temporally, respectively, while in the "tapered" method, the correction term is tapered to zero near bottom topography. In this study, the smoothed, mean, and tapered SPM's are combined (hereafter, the "modified" semi-prognostic method), using a smoothing scale of several model grid points and annual time averaging.

3. Model set-up and experiments

We use the FLAME ocean model (*Dengg et al.* [1999]) applied to the Atlantic Ocean from 18°S to 70°N with a horizontal resolution of 4/3° in longitude and 4/3°cosϕ in latitude (ϕ) with 45 unevenly spaced z-levels in the vertical. The model set-up and forcing (which is seasonal) are the same as in *Eden et al.* [2004] apart from (i) the different horizontal resolution, (ii) the use of the *Redi* [1982] isopycnal mixing scheme, (iii) the *Gent and McWilliams* [1990] scheme for tracer transport and (iv) the bottom boundary layer parameterization (BBL) of *Beckmann and Döscher* [1997] to represent the dense overflows across the sills in the subpolar North Atlantic. The isopycnal diffusivity and thickness diffusivity coefficients are set to 2×10^7 cm^{2}s^{-1}, decaying with depth to 0.5×10^7 cm^{2}s^{-1} below 4000 m. The background horizontal diffusivity (viscosity) is set to $10^6\cos\phi$ cm^{2}s^{-1} ($10^8\cos\phi$ cm^{2}s^{-1}) and the turbulent kinetic energy model of *Gaspar et al.* [1990] is used to calculate the vertical eddy diffusivity and viscosity. The climatological data used for the semi-prognostic method is a modification of that of *Boyer and Levitus* [1997].

To parameterize the net flux of CFC-12 at the sea surface we use

$$F = K(C_{sat} - C_{water}), \tag{4}$$

where $C_{sat} = A$ x $pCFC$, A is the solubility coefficient [*Warner et al.*, 1985], $pCFC$ is the partial pressure of CFC-12 in the atmosphere at the sea surface, C_{water} is the model-calculated concentration of CFC-12 at the surface of the ocean, and K is the piston velocity defined as [*Wanninkhof*, 1992]:

$$K = 0.39(S_c/660)^{-0.5}U_{wind}^2. \tag{5}$$

Here U_{wind} is the monthly mean wind speed at 10 m above the sea surface, and S_c is the Schmidt number. This is exactly the same parameterization as used by *Beismann and Redler* [2003] and allows use to make a direct comparison between their results are ours. The values for $pCFC$ are taken from *Walker et al.* [2000]. Due to rapid mixing in the lower atmosphere and the chemical stability of CFC-12, $pCFC$ is spatially uniform in each hemisphere except between 10°N and 10°S where the values are interpolated linearly as a function of latitude. Finally, the flux of CFC-12 through the northern and southern open boundaries and out of the Mediterranean is set to zero.

We describe results from two numerical experiments that differ only in that one is a standard prognostic calculation while the other uses the modified semi-prognostic method with $\alpha = 0.5$. Each experiment is first spun up for 20 years, after which the model is in a quasi-equilibrium state [*Willebrand et al.*, 2001]. Since most of the CFC-12 entered the atmosphere after 1950, the model simulations cover the period 1950-97.

4. Model results

Overall, the prognostic model results agree closely with *Beismann and Redler* [2003]. Figure 1 shows the simulated CFC-12 distribution corresponding to February of 1990 at 1875 m and 2375 m depth. Both model runs produce high concentrations in the Labrador Sea in response to the deep convection there. These high concentrations subsequently leak out to the rest of the North Atlantic, but in rather different ways in each case. In the prognostic model, the DWBC is detached from the continental slope, resulting in a high-concentration tongue in the basin interior. In the semi-prognostic run, the DWBC follows the continental slope, leading to a very different pattern of CFC-12 concentration. To check that the difference is not dependent on the tapering used for the semi-prognostic correction, we repeated the semi-prognostic run without using tapering and obtained the same result.

To assess the performance of the two model runs, we compare the simulated and observed CFC-12 concentrations along the WOCE hydrographic/tracer section A20 at 52°W (Figure 2). The CFC-12 concentrations were measured in July/August of 1997 and have three distinct sub-surface CFC-12-enriched water cores (Figure 2a; see *Smethie* [1999] for details). The shallowest high-concentration core, at about 280 m depth and between 16°N to 39°N, is associated with subtropical mode water. The two deeper sub-surface maxima are close to the continental slope. The core centered at about 1500 m north of 30°N is associated with Labrador Sea Water (LSW) and the core at about 4000 m near the bottom of the continental slope, is associated with the deep overflows. There is also a CFC-12 minimum at about 1000 m associated with Upper Circumpolar Water (UCW), which is far from its source region (the Southern Ocean) and hence has a low CFC concentration. Both the prognostic and modified semi-prognostic model runs reproduce reasonably well the overall features of the CFC-12 distribution. On the negative side, both show too strong a minimum in association with UCW (apparently the semi-prognostic method is not able to correct for this error) and both are missing the deep maximum associated with the overflows. On the other hand, both model runs reproduce the sub-surface maximum at about 2000 m depth associated with LSW, and it is here that the major difference between the two model runs is found. In particular, the sub-surface CFC-12 maximum produced by the modified semi-prognostic model is close to the continental slope, while the maximum produced by the prognostic model is away from the slope (as in Figure 1). Clearly, the semi-prognostic case compares much better with the observations.

Figure 3 compares the performance of the two models in the subtropics. Figure 3a,b show the concentration of CFC-12 along $24^o N$. Both model versions agree well above 1000 m, but below 1000 m, the semi-prognostic version shows a much stronger maximum in concentration associated with the DWBC. In both model versions, there is no net flux of CFC-12 to the south above 1000 m (as shown by the cumulative transport shown in Figure 3c), whereas below 1000 m, there is a 50% increase in the net southward transport of CFC-12 in the semi-prognostic compared to the prognostic model versions (Figure 3d), almost all of this increase being associated with the DWBC.

5. Summary and discussion

Poor representation of the concentration of CFCs in the DWBC region is a common problem in models of the North Atlantic [*England and Maier-Reimer*, 2001; *Dutay et al.*, 2002]. In this letter, we have shown that using the semi-prognostic method to add a correction to the model horizontal momentum equations ([*Greatbatch et al.*, 2004]) leads to a more realistic distribution of CFCs near the western boundary than is found in a companion prognostic model run. Whereas in the prognostic model, the DWBC separates from the western boundary, leading to an interior maximum in CFC concentration, in the semi-prognostic run, the DWBC follows the continental slope, leading to a concentration maximum near the boundary, and more in keeping with the observations. We note that the semi-prognostic method is well suited for use in tracer studies, because the correction to the model is added to the momentum equations, not the tracer equations. The semi-prognostic model also shows enhanced southward export of CFC-12 through $24^o N$ compared to the prognostic model run.

The failure of profiling floats released in the Labrador Sea to make their way southward along the western boundary [e.g. *Lavender et al.*, 2000; *Fischer and Schott*, 2002] has raised questions about exactly how Labrador Sea Water (LSW) spreads from its source region to the rest of the North Atlantic. The existence of a route along the western boundary, following the continental slope, is supported by the potential vorticity maps of *Talley and McCartney* [1982], as well as by tracer measurements [*Fine et al.*, 2002; *Smethie et al.*, 2000; *Smethie*, 1999, 1993]. Also, *Molinari et al.* [1998] detected LSW formed in the early 1990's near the Bahamas at $26.5^o N$, suggestive of a "fast track" along the western boundary from the Labrador Sea to the subtropics. These observations support the view that leakage of CFCs (and by inference LSW) does indeed take place along the continental slope, as in our semi-prognostic model run. Nevertheless, as can be seen from Figure 1, the interior pathway along the western side of the mid-Atlantic ridge is not eliminated in our semi-prognostic run, and there is increasing evidence from recent tracer measurements that this interior route is also operative in the North Atlantic (M. Rhein and D.Kieke, personal communication).

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R. J. Greatbatch, J. Sheng and J. Zhao, Department of Oceanography, Dalhousie University, Halifax, NS, Canada, B3H 4J1. (Jun.Zhao@dal.ca)

C. Eden, Ifm-GEOMAR, Kiel, Germany.

K. Azetsu-Scott, Bedford Institute of Oceanography, Dartmouth, NS, Canada, B2Y 4A2

(Received ______________________________.)

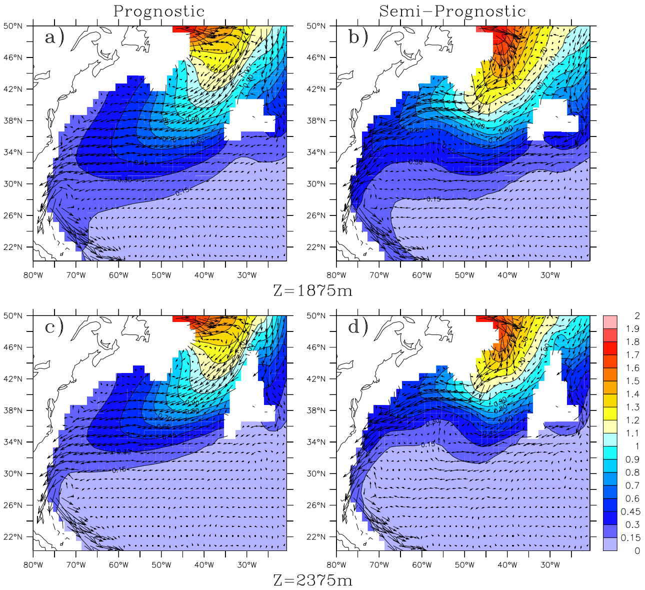

Figure 1. Monthly mean CFC-12 concentration in *pmol kg*$^{-1}$ (color image) and horizontal velocity (arrows) over the western subtropical Atlantic in February of year 1990 at 1875 m depth in (a) the prognostic model and (b) the modified semi-prognostic model. (c) and (d) are as for (a) and (b) but at 2375 m depth.

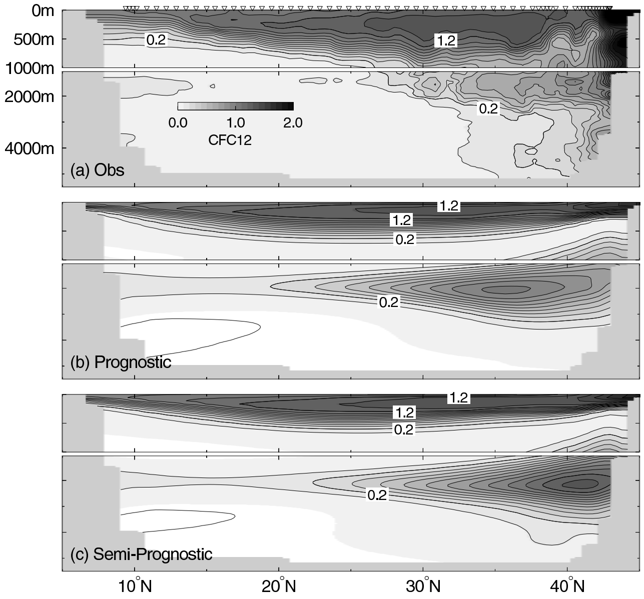

Figure 2. (a) The observed CFC-12 concentration in *pmol kg*$^{-1}$ along a meridional transect A20 at 52°W in the North Atlantic in July/August of 1997 redrawn from the data set described by *Smethie et al.* [2000]. The time-mean CFC-12 concentrations in *pmol kg*$^{-1}$ averaged from the model results over July and August of 1997 along the same transect for (b) the prognostic model and (c) the modified semi-prognostic model.

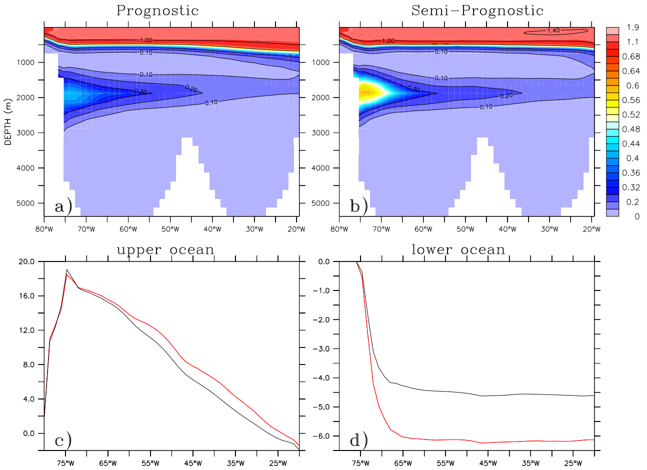

Figure 3. The concentration of CFC-12 along $24^o N$ in the (a) prognostic and (b) semi-prognostic model runs, corresponding to February 1997, in units of $pmol/kg$. (c) and (d) show the cumulative advective transport (positive northward) through $24^o N$ integrated eastwards from the western boundary for the upper (above 1000 m) and lower (below 1000 m) ocean in the prognostic (black) and semi-prognostic (red) model runs in units of $10^{-3} mol/s$.