

Using chlorofluorocarbons to assess ocean climate models

Matthew H. England¹

CSIRO Division of Oceanography, Hobart, Australia

Abstract. The potential for using chlorofluorocarbons (CFCs) to assess ocean climate models is explored within a series of global ocean experiments. The ocean model simulations are run under identical wind stress and thermohaline forcing, but with three different formulations of subgrid-scale mixing. Two passive tracers are included in the equilibrated models, representing the dissolved concentrations of CFC-11 and CFC-12 in seawater. The resulting model simulations are then compared directly with observed CFC levels in key areas for deep and bottom water formation. CFC-11 uptake is found to be overestimated in the Southern Ocean when mixing rates are defined in traditional Cartesian co-ordinates. The inclusion of an isopycnal mixing scheme (which is often used in coupled ocean-atmosphere models) actually degrades the CFC-11 simulation by blending water masses too strongly, particularly in the Southern Ocean. The spurious uptake of CFC-11 at 55°–70°S suggests that certain climate models might overestimate the role of the Southern Ocean in moderating climate change. A more sophisticated mixing parameterization that simulates the effects of subgrid-scale eddies on the mean ocean flow (and allows for zero lateral diffusion) is seen to greatly reduce CFC-11 uptake in the Southern Ocean. Climate models that adopt this new mixing scheme are likely to predict a more rapid CO₂-induced warming over the Southern Hemisphere.

Introduction

The industrial release of chlorofluorocarbons (CFCs) began in the early 1930s, and accelerated greatly during the next three decades (Fig. 1). Because CFCs are weakly soluble in seawater, they get dissolved at the sea surface like most other atmospheric gases. Upper level traces of CFC then get redistributed vertically by convection and subduction, and horizontally by interior ocean currents and mixing. Recently ventilated waters are therefore characterized by comparatively high concentrations of these gases. Seawater CFC concentrations can now be measured with relative ease (Bullister and Weiss 1988). In observational oceanography, direct ocean measurements of dissolved CFC are often used to add information to conventional hydrographic data. Until recently, modelers have not fully exploited the potential for using CFCs to assess general circulation models of the ocean.

In this letter we report the results of three different simulations of the uptake and redistribution of CFC-11 in a global ocean model. A similar study has been undertaken independently by Robitaille and Weaver (1995), although different

analysis techniques have been used. The experimental cases differ only in the parameterization of subgrid-scale mixing, yet each simulation differs markedly in its distribution of dissolved CFC, particularly in the Southern Hemisphere. The implications of these findings for coupled ocean-atmosphere models and estimates of the ocean carbon cycle are discussed.

The ocean model and CFC forcing

The ocean model studied is the primitive equation model of Bryan (1969) and Cox (1984) configured over a global domain with a realistic representation of continental outlines and bottom bathymetry (further model details can be found in England et al. 1994). The upper level thermohaline and wind stress forcing is derived from standard climatological data sets and includes a complete seasonal cycle. Because of coarse horizontal grid spacing (3.75° longitude by 4.5° latitude), the effects of mesoscale eddies must be parameterized in some way.

Under identical surface boundary conditions and in the same basic model geometry, three different mixing schemes are considered. The first case (denoted *Control*) adopts traditional Cartesian mixing (as in Toggweiler et al. 1989) with diffusion taking place in strictly horizontal and vertical directions. The second case (*Isopycnal*) includes an isopycnal mixing scheme (as in Manabe et al. 1991, England 1993) whereby diffusion rates are enhanced in an along-isopycnal sense and horizontal mixing is reduced slightly (though maintained for numerical stability). This case has identical geometry and mixing parameterization to the uncoupled ocean model of Manabe et al. (1991). The final case (*GM-mixing*) adopts the recently formulated parameterization of the effects of eddies on the mean ocean flow (as proposed by Gent et al. 1995), which allows for zero lateral diffusion whilst enhancing mixing in an along-isopycnal sense. This mixing scheme has recently been

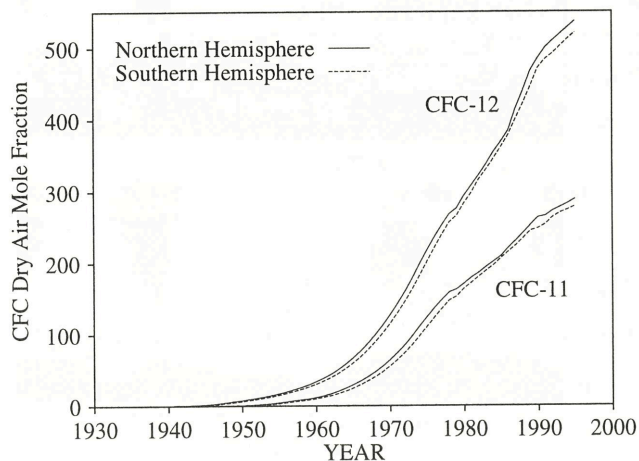


Figure 1. Reconstructed history of the atmospheric dry air mole fractions of CFC-11 and CFC-12 (in ppt) for the Northern and Southern Hemispheres.

¹Presently at the School of Mathematics, the University of New South Wales, NSW, 2052 Australia. (e-mail: M.England@unsw.edu.au)

Copyright 1995 by the American Geophysical Union.

Paper number 95GL02670

0094-8534/95/95GL-02670\$03.00

shown to have several beneficial effects on the steady-state model solution, although its role in determining transient ocean ventilation rates remains largely unexplored.

The air-sea exchange of CFCs is forced using the standard gas flux law with a wind-speed and Schmidt number dependent gas piston velocity (following Wanninkhof 1992). Total or partial sea-ice cover limits gas exchange in direct proportion to the observed seasonally-varying sea-ice coverage in the Arctic and Southern Oceans. This method of forcing the air-sea gas transfer reproduces observed trends in surface CFC concentrations; namely, undersaturation in regions of deep convective overturn, sea-ice cover or near-surface upwelling, and supersaturation in the summer mixed layer (England et al. 1994).

CFC uptake in the Southern Ocean

Ocean models typically simulate 10 to 20 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3/\text{sec}$) of bottom water formation off the Antarctic shelf (e.g., England 1993), which is not dissimilar to actual estimates of net Antarctic Bottom Water production. However, the models can represent the bottom water formation as very deep open ocean convection, depending on the chosen parameterization of subgrid-scale mixing. Figure 2 shows the maximum surface layer convection depth in each of the three experiments over the Southern Hemisphere. Included in Figs. 2b and 2c are those regions where the slope of the isopycnal surfaces exceeds 1 part in 100 (corresponding to the maximum slope set for isopycnal diffusion), which generates vertical diffusion terms that partly mimic and replace explicit convective mixing. The GM-mixing case largely limits convection to the

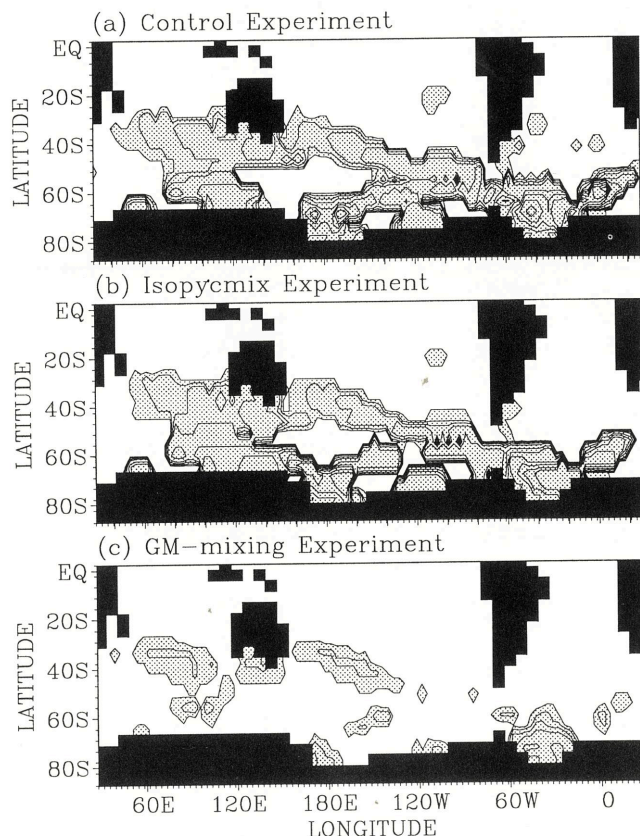


Figure 2. Maximum depth of surface level convective overturn during an annual cycle of the equilibrated model runs. Contours are drawn at depths of 120-m, 240-m, 400-m, 600-m, 1000-m, 1400-m, 1900-m, 2600-m, 3400-m and 4200-m.

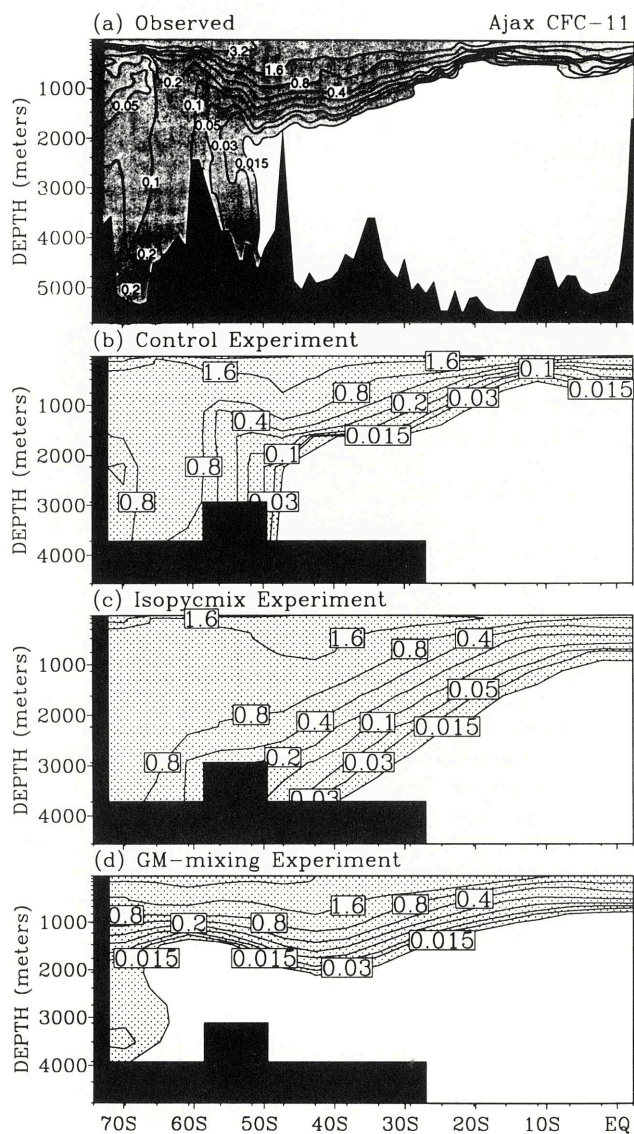


Figure 3. Latitude-depth sections of dissolved CFC-11 at the Greenwich meridian during late 1983 (pmol/kg). (a) Observed Ajax section, redrafted from Warner and Weiss (1992), (b) Control, (c) Isopycmix, and (d) GM-mixing experiments.

Antarctic shelf and north of the polar frontal zone (both thought to be regions of convective mixed layer formation). In the other two cases, very deep surface layer overturn is simulated at 55° - 70° S, a band of latitude normally characterized by upwelling of old circumpolar deep water (CDW) and shallow surface mixed layers. This striking contrast between observed and modeled circulation, whereby the model suggests rapid local overturn in a region thought to witness deep upwelling of old water, is likely to generate quite erroneous CFC simulations in the Control and Isopycmix cases.

To explore this issue, observed and modeled CFC-11 concentrations are shown along the Greenwich meridian in Fig. 3. Marked differences between the model cases and observations appear south of 40° S. For example, note the location of the 0.8 pmol/kg contour south of 60° S: in the observed section it remains in the upper 400-m of the water column, whereas it reaches the bottom of the ocean in the Control and Isopycmix cases. This suggests that the model convective overturn and

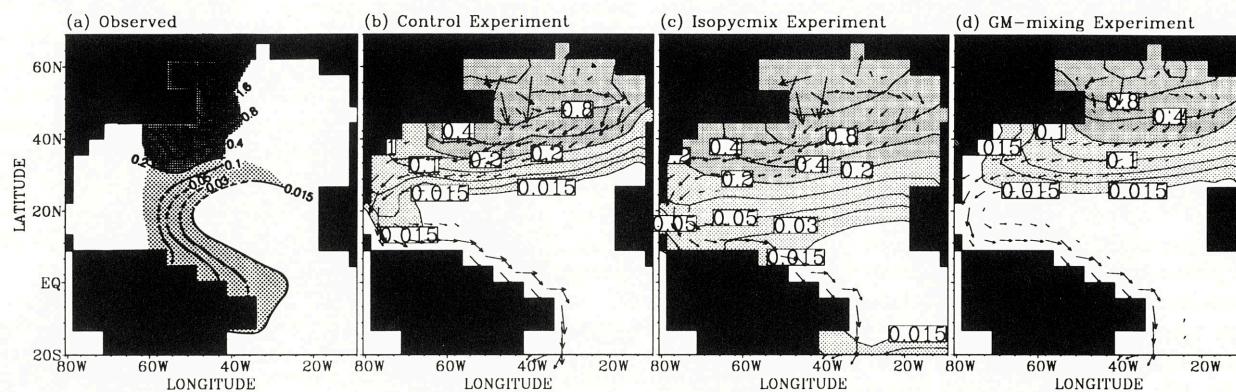


Figure 4. (a) Observed concentration of CFC-11 in the core of Upper NADW during 1982, redrafted from Weiss et al. (1985). (b)-(d) Corresponding model currents and dissolved CFC-11 at 1622-m depth. Currents weaker than 0.1 cm/sec are not shown.

vertical mixing is too strong in these runs, particularly at 55°–70°S. The intensity of surface level overturn is because insufficient CDW recirculates and upwells into the Southern Ocean (the observed Ajax section suggests that CDW upwells into the upper 1000-m near 60°S). More upwelled CDW (being CFC-deprived) would weaken the upper ocean CFC-11 concentrations substantially, not only because the older water would contribute to a lower CFC mixture, but also because the local convective activity would be weakened by the presence of realistically dense water at the deeper model levels.

The inclusion of the isopycnal mixing scheme actually degrades the model simulation of CFC-11 over the Southern Ocean (Fig. 3c, additional meridional sections have been analysed at other cruise locations). Experiments with weaker along-isopycnal mixing rates also show a similar pattern of erroneous surface water ventilation in the region. Therefore, even though isopycnal mixing can improve the model representation of certain water masses (England 1993), it can also lead to unrealistically strong mixing in other regions of the ocean. This will occur if the model stratification is too weak, or if the simulated density structure is erroneous. Ultimately the enhanced isopycnal mixing is only desirable if the model can simulate the observed ocean density structure realistically, otherwise the extra mixing terms act to increase the diffusion of water properties in an already over-diffusive model.

The GM-mixing case shows greatly reduced CFC uptake over the Southern Ocean, with only a weak signature of bottom water crossing the Ajax section near 3500-m depth. Additional analysis of the model simulation shows how this water mass originates directly from Weddell Sea Shelf Water. The observed CFC section also suggests a remote formation site for this bottom water mass (note the isolated 0.2 pmol/kg water at depth). This contrasts the Control and Isopycnal cases, where local surface waters make a significant contribution to the bottom water along the Ajax section (see also Fig. 2). The GM-mixing case is therefore the most realistic in representing the actual bottom water formation processes operating in the Southern Ocean, partly because lateral diffusion rates are set to zero, enabling relatively undiluted bottom water to be formed off the Antarctic shelf.

CFC uptake in the North Atlantic Ocean

Significant levels of dissolved CFC-11 were first detected in outflowing North Atlantic Deep Water (NADW) by Weiss et al. (1985; see Fig. 4a). Their measurements confirm the presence

of CFC-enriched deep waters at the western boundary of the tropical Atlantic during 1983. The corresponding maps of simulated CFC-11 in the three model experiments are included in Fig. 4. Each of the three simulations have weaker CFC-11 concentrations in the western boundary outflow compared with the real ocean. In effect the model southward extension of CFC-enriched upper NADW does not match observations. This is because the time-scale for NADW outflow is too slow compared with the real ocean. The long time-scale is partly due to unrealistically sluggish deep currents. In addition, part of the path of NADW outflow includes a questionable loop eastward from the Labrador Sea into the Northeastern Atlantic Basin (Fig. 4), effectively increasing the required outflow journey by around 4000-km. The additional circulation eastward ages the water mass by at least ten years (depending on the speed of the model ocean currents), thereby yielding significantly lower CFC concentrations in the NADW extension.

The outflowing CFC-11 signal is too diffuse in the Isopycnal run, having little zonal structure even though the outflow currents are predominantly at the western boundary. Model data sampled during later years show that both the Control and GM-mixing cases simulate an outflowing signal along the

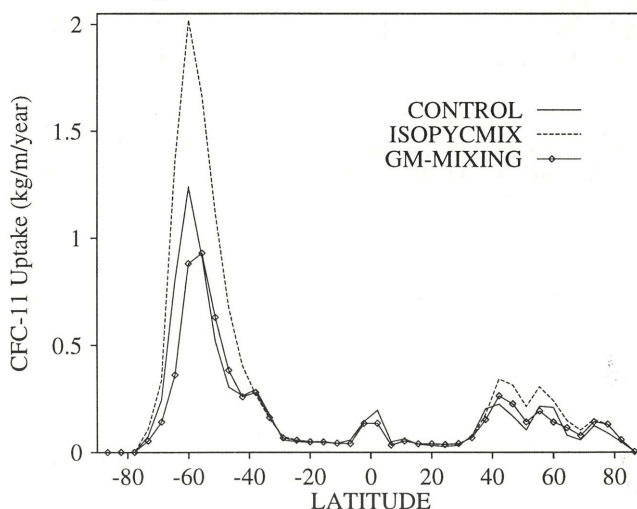


Figure 5. Zonally-integrated air-sea flux of CFC-11 in the three model experiments during 1983 (kg/m/year). Similar latitudinal variations are noted during other years, since the ocean model circulation exhibits little interannual variability.

western boundary of the deep Atlantic, whereas the Isopycnal experiment diffuses much of this signal eastward. Clearly the inclusion of an isopycnal mixing scheme can introduce significant errors in the simulated ventilation of the ocean model.

Implications for climate models and the ocean carbon cycle

In coupled climate models a substantial amount of heat can be absorbed and redistributed by the ocean. If surface waters are overturned too rapidly, a climate change model will predict too slow a warming of the lower atmosphere because much of the enhanced warmth will be overturned within the ocean. It is therefore critical that ocean models represent the vertical circulation and uptake of atmospheric properties realistically.

A measure of the strength of surface water overturn is provided by the net flux of CFC-11 into the ocean. A strong absorption of CFC indicates that surface waters are being drawn down rapidly, since then the upper ocean becomes undersaturated in CFC-11, enabling increased ocean uptake of the gas. Figure 5 shows a plot of the zonally-integrated air-sea flux of CFC-11 in each of the three experiments during 1983. Little variation in CFC uptake is seen at low latitudes, whereas quite substantial differences are noted over the Southern Ocean. In particular, the net CFC-11 uptake over the Southern Hemisphere in the GM-mixing experiment is about half that of the Isopycnal case. A climate model simulation of CO₂-induced warming that adopts the GM-mixing scheme is therefore likely to exhibit less deep ocean absorption of heat over the Southern Ocean - simply because the corresponding model circulation shows slower overturn and ventilation in this region. In a similar manner, model-derived estimates of the ocean carbon cycle could be largely determined by the choice of subgrid-scale mixing scheme.

Conclusions

Soluble anthropogenic gases provide clear tracers of recently ventilated waters in the ocean interior. Ocean modelers can exploit emerging CFC data by evaluating relatively short model integrations of gas uptake over the ocean. The comparison between observed and simulated CFC then provides direct information about the reliability of the ocean model in reproducing realistic rates of surface water overturn and interior water ventilation. This process of ocean model assessment is critical in the context of coupled ocean-atmosphere modelling and in efforts to understand the earth's climate system.

An ocean model configured to be similar to that used in recent climate studies was shown to overestimate the uptake of CFC over the subpolar Southern Ocean when conventional Cartesian or isopycnal mixing schemes are adopted. Climate change predictions in coupled models could therefore be unreliable in the Southern Hemisphere, since all have incorporated

one of these two mixing schemes. In particular, the finding that the earth's climate responds slowly to greenhouse warming over the Southern Ocean might be partly due to a spurious uptake of heat over the circumpolar waters. The results of our study suggest that the interhemispheric asymmetry in warming predicted by climate change models will be somewhat reduced under the Gent et al. (1995) scheme. Coupled models that adopt this more sophisticated mixing parameterization are likely to predict a more rapid warming rate over the Southern Hemisphere.

Acknowledgements. This study contributes to the CSIRO Climate Change Research Program and was partly funded by Australia's National Greenhouse Research Program. Drs. K. Dixon, A.C. Hirst, T.J. McDougall and S.R. Rintoul contributed with helpful discussions.

References

- Bryan, K., A numerical method for the study of the circulation of the World Ocean. *J. Comput. Phys.*, 3, 347-376, 1969.
- Bullister, J.L., and R.F. Weiss, Determination of CCl₃F and CCl₂F₂ in seawater and air. *Deep Sea Res.*, 35, 839-853, 1988.
- Cox, M.D., A primitive equation, three-dimensional model of the ocean. *GFDL Ocean Group Tech. Rep. No. 1*, 143 pp, 1984.
- England, M.H., Representing the global-scale water masses in ocean GCMs. *J. Phys. Oceanogr.*, 23, 1523-1552, 1993.
- England, M.H., V.C. Garçon, 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.
- Gent, P.R., J. Willebrand, T.J. McDougall, and J.C. McWilliams, Parameterizing eddy-induced tracer transports in ocean circulation models, *J. Phys. Oceanogr.*, 25, 463-474, 1995.
- Manabe, S., R.J. Stouffer, M.J. Spelman, and K. Bryan, Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric carbon dioxide. Part I: Annual mean response. *J. Climate*, 4, 785-818, 1991.
- Robitaille, D.Y., and A.J. Weaver, Validation of sub-grid scale mixing schemes using CFCs in a global ocean model. *Geophys. Res. Lett.*, (this issue), 1995.
- Toggweiler, J.R., K. Dixon, and K. Bryan, Simulations of radiocarbon in a coarse-resolution world ocean model. I: Steady state prebomb distributions. *J. Geophys. Res.*, 94, 8217-8242, 1989.
- Wanninkhof, R., Relationship between wind speed and gas exchange over the ocean. *J. Geophys. Res.*, 97, 7373-7382, 1992.
- Warner, M.J., and R.F. Weiss, Chlorofluoromethanes in South Atlantic Antarctic Intermediate Water. *Deep Sea Res.*, 39, 2053-2075, 1992.
- Weiss, R.F., J.L. Bullister, R.H. Gammon and M.J. Warner, Atmospheric chlorofluoromethanes in the deep equatorial Atlantic. *Nature*, 314, 608-610, 1985.

M.H. England, CSIRO Division of Oceanography, GPO Box 1538, Hobart, 7001, Tasmania, Australia. (e-mail: mhe@dar.csiro.au)

(Received January 20, 1995; revised June 6, 1995; accepted August 18, 1995)