Examining a coupled climate model using CFC-11 as an ocean tracer

Keith W. Dixon,[1] John L. Bullister,[2] Richard H. Gammon,[3] and Ronald J. Stouffer[1]

Abstract. Anthropogenic CFC-11 dissolved in seawater is used to analyze ocean ventilation simulated in a global coupled air-sea model. Modeled CFC-11 distributions are compared to observations gathered on three Southern Hemisphere research cruises. The total amount of CFC-11 absorbed by the model's Southern Ocean is realistic, though some notable differences in the vertical structure exist. Observed and simulated CFC-11 distributions are qualitatively consistent with the coupled model's predictions that the ocean may delay greenhouse gas-induced warming of surface air temperatures at high southern latitudes. The sensitivity of model-predicted CFC-11 levels in the deep Southern Ocean to the choice of gas exchange parameterization suggests that quantitative assessments of model performance based upon simulated CFC-11 distributions can be limited by air-sea gas flux uncertainties in areas of rapid ocean ventilation. Such sensitivities can complicate the quantitative aspects of CFC-11 comparisons between models and observations, and between different models.

Introduction

In this letter, we examine the ocean component of a global coupled air-sea model developed at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). The model's control state and its transient responses to gradual changes of atmospheric CO_2 have been reported previously [e.g., *Manabe et al.*, 1991; *Manabe and Stouffer*, 1994]. Of particular interest is the interhemispheric asymmetry in the response of modeled surface air temperatures to increasing CO_2, with exceptionally slow warming simulated south of ~45°S. This asymmetry is attributed primarily to the Southern Ocean's large effective thermal inertia, an effect which is the product of the Southern Hemisphere's large ocean surface area, and deep and rapid mixing in the model's Southern Ocean.

Here we inspect the ocean component of the GFDL coupled model's control simulation (constant CO_2) using anthropogenic trichlorofluoromethane (CCl_3F or CFC-11) as a tracer of ocean ventilation. By comparing modeled CFC-11 transient tracer distributions to observations, we seek to assess whether the simulated oceanic ventilation largely responsible for the uptake of excess greenhouse heat in the model's Southern Hemisphere is plausible. Additionally, by using different gas exchange parameterization schemes, we examine the sensitivity of modeled tracer distributions to the manner in which CFC-11 air-sea fluxes are specified.

Accurate techniques to measure oceanic chlorofluorocarbons (CFCs) were developed in the early 1980s [*Gammon et al.*, 1982]. Since then, oceanographers have gathered and analyzed a substantial quantity of CFC data (for an overview see *Bullister* [1989]). The

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[1] NOAA, Geophysical Fluid Dynamics Laboratory, Princeton, NJ.
[2] NOAA, Pacific Marine Environmental Laboratory, Seattle, WA.
[3] Chemistry Department and School of Oceanography, University of Washington, Seattle, WA.

feasibility of using CFCs as analysis aids in global ocean general circulation models (GCMs) has been demonstrated recently [e.g., *England et al.*, 1994; *Robitaille and Weaver*, 1995; *England*, 1995].

Model Description and Experimental Design

Details of the GFDL coupled model's construction are found in *Manabe et al.* [1991]; hence, only a brief summary of the model configuration is given below, followed by a description of how CFC-11 is incorporated into the ocean model component.

The GFDL coupled climate model incorporates three-dimensional GCMs of the global ocean and atmosphere with simpler land hydrology and sea ice models. Seasonally varying insolation drives the coupled model, with air-sea heat and freshwater flux adjustments included to reduce climate drift. The atmospheric spectral model uses rhomboidal 15 truncation and has 9 vertical levels. Atmospheric CO_2 levels are prescribed to be time invariant in this configuration. The sea ice model predicts sea ice thickness, but not fractional coverage. The global ocean model has ~4.5° latitude by 3.75° longitude grid spacing, 12 vertical levels and a maximum depth of 5000m. The rotated diffusion tensor method described by *Cox* [1987] is used to parameterize the mixing of heat, salinity and passive tracers by unresolved ocean motions.

Using the following relationship, a CFC-11 air-sea flux (F) is calculated at each ocean surface grid cell every model timestep.

$$F = \alpha \; \kappa(Sc, |V|) \; [C_e(C_a, T, S) - C_w] \qquad (1)$$

CFC-11 air-sea fluxes are directly proportional to the difference between model-predicted levels of CFC-11 dissolved in surface water (C_w) and local seawater saturation equilibrium values (C_e). C_e values are the product of atmospheric CFC-11 levels (C_a) and CFC-11 seawater solubilities [*Warner and Weiss*, 1985] at model-predicted sea surface temperatures (T) and salinities (S). C_w approaches C_e at a rate set by the local gas transfer (piston) velocity (κ). Values of κ are calculated as a function of the atmospheric model's daily mean surface wind speed $(|V|)$ and water temperature dependent Schmidt numbers $(Sc(T))$. The influence of sea ice on CFC-11 air-sea fluxes is represented by α in equation (1).

Because this study's principal goal is to examine ventilation pathways associated with the ocean model's uptake of excess greenhouse heat, we seek to simulate CFC-11 air-sea fluxes in a manner consistent with the coupled model's computation of air-sea sensible heat and evaporative fluxes via bulk formulae. Thus, CFC-11 air-sea fluxes are computed using model-predicted T, S, $|V|$ and sea ice fields rather than values derived from observational climatologies. This consistency is maximized by setting α in a binary manner (i.e., $\alpha=1$ at ice-free grid cells and $\alpha=0$ at grid cells where model-predicted sea ice thicknesses are greater than zero).

Time varying C_a values are prescribed (the atmospheric GCM does not carry CFC-11 as a prognostic tracer). Tropospheric CFC-11 levels have increased rapidly since production began in the 1930s. Direct measurements of C_a were not made before the late 1970s; however, earlier tropospheric CFC-11 levels can been deduced from production/release data and CFC-11's atmospheric lifetime. *Warner and Weiss* [1992] discuss the relatively small magnitude of errors associated with such reconstructions.

The equilibration time-scale ($\Delta z/\kappa$, where Δz is the ocean's mixed layer depth) for CFCs in the ocean's mixed layer to adjust to atmospheric levels is typically less than one month. But uncertainties exist concerning how κ varies as a function of environmental variables. The model's sensitivity to uncertainties in κ is examined by comparing CFC-11 distributions simulated using two different parameterization schemes; namely the relationships of *Liss and Merlivat* [1986] and equation 3 of *Wanninkhof* [1992] (hereafter LM86 and W92, respectively). The W92 equation yields larger κ values than do the LM86 relationships. As noted in W92, factors not directly linked to local wind speed (e.g., fetch, bubble entrainment, surfactants) influence air-sea gas transfer, so schemes such as these that rely on only W and Sc to estimate κ are likely to be flawed.

We initialize our experiments from year 1000 of the *Stouffer et al.* [1994] standard run. The entry and redistribution of CFC-11 in the ocean are simulated for the period 1930 to 1994. In other words, for CFC-11 purposes, model year 1000 is considered to be 1930. The GFDL coupled model does not attempt to replicate the historical climate variability of specific months or years. Rather, the model internally generates its own variability as its external forcings (top of the atmosphere insolation and the surface flux adjustments) exactly repeat the same seasonal cycles each year.

Results and Discussion

Much more CFC-11 uptake occurs in the ocean model's Southern Hemisphere than in the Northern Hemisphere (Figure 1). Much of this interhemispheric asymmetry in the zonally integrated CFC-11 air-sea fluxes arises from the distribution of land and sea; the area over which large CFC-11 surface fluxes are simulated in the Southern Ocean is greater than that found in the Northern Hemisphere's higher latitudes. The interhemispheric asymmetry pattern evident in the simulated CFC-11 uptake is qualitatively similar to that seen in the GFDL coupled model's oceanic uptake of greenhouse heat [*Manabe et al.*, 1991].

Coupled model results computed using the gas exchange relationships of LM86 and W92 also appear in Figure 1, and reveal that CFC-11 air-sea fluxes are most sensitive to κ variations in high latitude regions marked by deep mixing and large CFC-11 air-sea fluxes. The LM86 relationships yield a globally averaged κ value
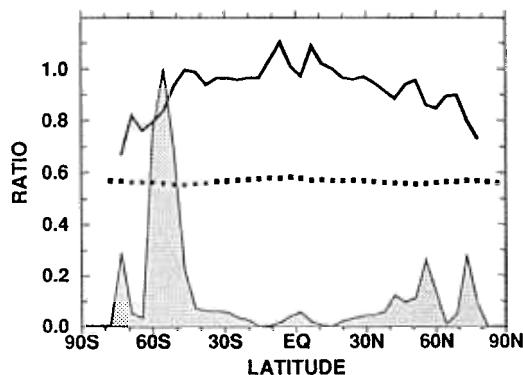

Figure 1. Solid Line: Zonally averaged CFC-11 air-sea flux ratios (F simulated using LM86 divided by F simulated using W92). Dashed line: Zonally averaged CFC-11 gas exchange velocity ratios (LM86 κ divided by W92 κ). Gray-filled area: Normalized, zonally integrated CFC-11 surface input from the W92 simulation (the product of F and the distance along a latitude circle covered by ocean). Surface inputs are normalized so the largest equals 1.0. Data are averaged over the 10-year model period 1981 through 1990.
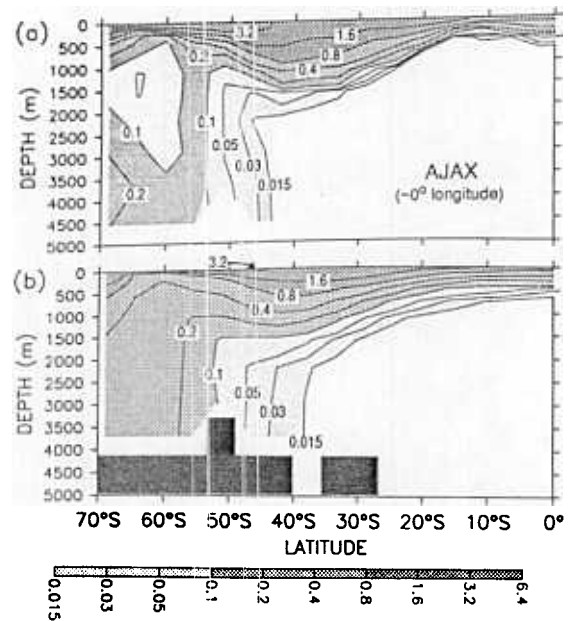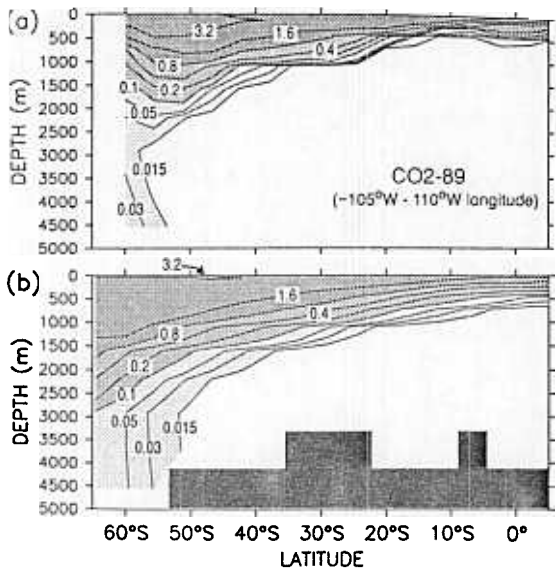

Figure 2. (a) CFC-11 concentrations (pmol kg^{-1}) measured along the Ajax prime meridian cruise track in Oct. 1983 and Jan. 1984 [*Weiss et al.*, 1990]. (b) CFC-11 levels along the Ajax track as simulated by the coupled model using the W92 gas exchange equation.

that is 57% of that produced by the W92 equation. The difference in the global mean net air-sea CFC-11 flux produced by the two formulations is smaller (the LM86 global mean F is 88% that of the W92 value); however, much more variability exists in the zonally averaged F ratios than in the κ ratios. The F ratios are closer to unity than are the κ ratios because larger air-sea fluxes associated with increased κ tend to keep surface CFC-11 levels closer to saturation (i.e., reduce $|C_e - C_w|$), which in turn reduce F. This effect is most efficient where ocean mixed layer depths are shallow. It follows that the sensitivity of F to κ is greatest where substantial and persistent CFC-11 undersaturation occurs in surface waters.

At various model locations south of ~50°S, convection, vertical advection, and/or mixing along steeply sloping isopycnals contribute to sizable CFC-11 surface undersaturation. So, it is not surprising that, where CFC-11 penetrates below 1500m depth in the model's Southern Hemisphere, CFC-11 levels simulated using LM86 are only ~65% to 75% that of W92-predicted values. Taking the difference between LM86 and W92 as representative of the uncertainty associated with estimating κ, these results suggest that detailed quantitative analyses comparing modeled and observed CFCs can be limited when a water parcel's CFC content is influenced by rapid ventilation involving markedly undersaturated surface waters.

Observed and simulated CFC-11 distributions associated with three research cruises are presented in Figures 2, 3 and 4. The one Atlantic (Ajax) and two Pacific (CO2-89 and CGC-90) cruises each traversed a large latitude range of the Southern Hemisphere. For comparative purposes, observed values were interpolated to the coarser model grid before plotting, and thus represent the best results the model could obtain, given its grid spacing.

A gross overall pattern is apparent in the three observed sections. In the southernmost portions of the sections, relatively high CFC-11 levels penetrate to the bottom, indicative of dense Antarctic bottom waters spreading downward and then northward. Farther north in the Southern Ocean, CFC-11 laden Antarctic Inter-

Figure 3. (a) CFC-11 concentrations (pmol kg^{-1}) measured along the CO2-89 cruise track (~105°W-110°W) during February and March 1989 [*Wisegarver et al.*, 1993]. (b) CFC-11 levels along the CO2-89 cruise track as simulated by the coupled model using W92.

mediate Water (AAIW) extends downward and northward from the surface to intermediate depths. Equatorward of ~30°S, tracer penetration is shallow. The observed pattern of deep CFC-11 penetration in the Southern Ocean is broadly consistent with the coupled model results, and supports the thesis that extensive Southern Hemispheric ocean ventilation could delay greenhouse gas induced warming of surface air temperatures in that region.

The CFC-11 comparisons expose some model deficiencies, such as insufficient AAIW formation and the lack of midwater CFC-11 minima at high southern latitudes (the latter partly arises from excessive diapycnal mixing in areas of steeply sloping isopycnals). Yet, good agreement exists between observed and modeled
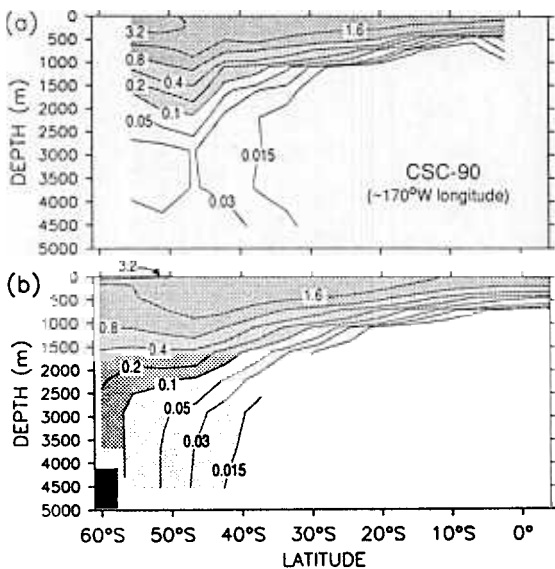

Figure 4. (a) CFC-11 concentrations (pmol kg^{-1}) measured along the CSC-90 cruise track (~170°W) in February through April 1990. [*Wisegarver et al.*, 1995]. (b) CFC-11 levels along the CSC-90 cruise track as simulated by the coupled model using W92.

vertically integrated CFC-11 column inventories (Figure 5). That the total amount of CFC-11 residing in the model's southern latitudes resembles the observations indicates that the simulated ventilation's cumulative, large-scale effect is reasonable, although partly the result of compensating errors. For example, lower than observed CFC-11 levels in the upper portion of the model's Southern Ocean (~300m to ~700m depth) largely compensate excessive CFC-11 levels predicted at greater depths.

Our findings differ from those of two recent uncoupled ocean GCM studies (*Robitaille and Weaver* [1995] and *England* [1995], hereafter RW95 and E95) which independently investigated simulations of Southern Ocean ventilation using CFC-11 as a tracer. In both the RW95 and E95 studies, simulated CFC-11 uptake along the southern portion of the Ajax cruise track was overestimated when Cox's isopycnal mixing parameterization was used. Here, the GFDL coupled model's CFC-11 levels along the Ajax section (Figure 2b) are markedly less than those simulated by the E95 ocean GCM that used the Cox isopycnal mixing scheme. When using Cox's scheme, CFC-11 concentrations along RW95's simulated Ajax section lie between the E95 and our coupled model results.

Absent a detailed model intercomparison, the source of model-to-model differences in CFC-11 distributions can not be identified with certainty. However, we offer two broad categories of possible causes as likely candidates. The first being differences in modeled ocean circulation and water mass formation rates and the second being differences in the parameterized CFC-11 air-sea fluxes.
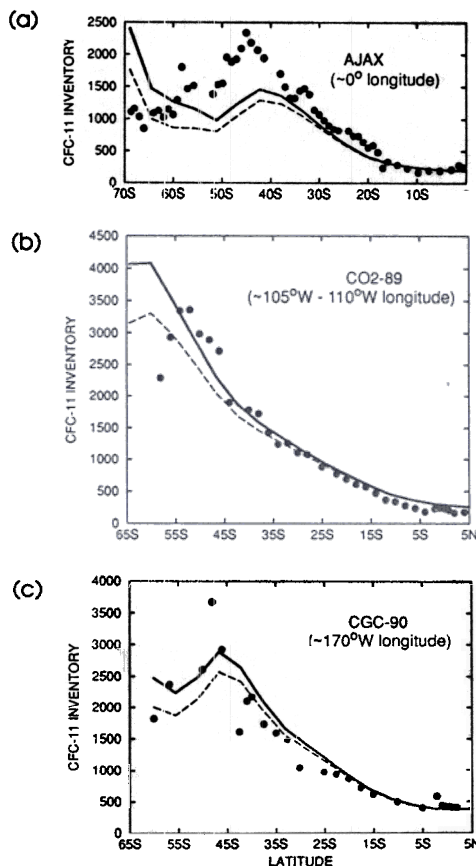
Figure 5. CFC-11 column inventories (nanomol m^{-2}) along three cruise tracks (a) Ajax cruise, (b) CO2-89 cruise, (c) CGC-90 cruise. Filled circle: column inventories calculated from observations. Dashed Line: model-predicted inventories computed using LM86. Solid Line: model-predicted inventories computed using W92.

Ocean circulation and ventilation patterns may vary significantly among the models due to differences in surface forcings (buoyancy and momentum) and subgrid-scale mixing coefficients. For example, winds over the coupled model's Southern Ocean are weaker than the observed winds used as boundary conditions in the E95 and RW95 studies. Weaker winds can lead to less meridional overturning (a weaker Deacon Cell) and reduced vertical transports of CFC-11. This is consistent with the RW95 finding that CFC-11 uptake is reduced when using a subgrid-scale mixing scheme that largely negates tracer advection associated with the Deacon Cell.

The coupled model's weak Southern Ocean winds yield lower κ values than those used in the E95 and RW95 studies, thus contributing to reduced CFC-11 uptake. Also, deep ocean CFC-11 concentrations may be sensitive to the treatment of how sea ice affects F, the air-sea gas exchange. In the RW95 and E95 studies, CFC-11 surface fluxes were reduced according to the observed fractional sea ice coverage data, which would allow larger CFC-11 inputs than the binary method of setting α used in this study.

Conclusions and Plans for Future Work

The integrated oceanic uptake of CFC-11 in the GFDL coupled model's Southern Hemisphere is in general agreement with observations. To the extent that CFC-11 uptake may be considered analogous to the transient uptake of excess greenhouse heat, this supports the interhemispheric asymmetry in greenhouse warming result of Manabe et al. [1991]. Observational evidence of deep CFC-11 penetration in the Southern Ocean also leads us to infer that an interhemispheric asymmetry in greenhouse gas induced warming of surface temperatures is quite plausible in the real climate system, and that it is not merely a model artifact.

There is insufficient evidence to suggest that the specific mechanisms responsible for the GFDL coupled model's uptake of transient greenhouse heat have been verified. Rather, comparisons of the coupled model's CFC-11 distributions to observations, and to previous uncoupled model studies, suggest that the GFDL coupled model's ocean may be taking up about the right amount of CFC-11 for some wrong reasons. We speculate that the coupled model's weak winds and restrictive sea ice treatment counter a tendency for Cox's isopycnal mixing scheme to overventilate. To investigate this, a suite of coupled model runs using various combinations of model-predicted and observed variables to compute CFC-11 air-sea fluxes is planned (although such gas fluxes are inconsistent with the model's surface heat flux computations).

The demonstrated sensitivity of high latitude CFC surface fluxes to variations in gas transfer velocities raises the question of to what degree present models can simulate these air-sea gas fluxes in regions of rapid ocean ventilation with sufficient accuracy to allow detailed *quantitative* assessments of model performance based on comparisons of observed and simulated CFC distributions. For this reason, and since the CFC-11 and excess greenhouse heat transients are not completely analogous, the CFC-11 analyses do not allow us at present to draw definite conclusions concerning the magnitude of the greenhouse warming interhemispheric asymmetry.

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K. W. Dixon and R. J. Stouffer, NOAA/GFDL, PO Box 308, Princeton, NJ 08542 (e-mail: kd@gfdl.gov ; rjs@gfdl.gov)

J. L. Bullister, NOAA/PMEL, 7600 Sand Point Way NE, Seattle, WA 98115 (e-mail: bullister@pmel.noaa.gov)

R. H. Gammon, Chemistry Dept, Univ. Washington, 109 Bagley, BG-10, Seattle, WA 98195 (e-mail: gammon@macmail.chem.washington.edu)