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Sensitivity of CFC-11 uptake to physical initial conditions and interannually varying surface forcing in a global ocean model

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ABSTRACT

Sensitivity of the oceanic chlorofluorocarbon CFC-11 uptake to physical initial conditions and surface dynamical forcing (heat and salt fluxes and wind stress) is investigated in a global ocean model used in climate studies. Two different initial conditions are used: a solution following a short integration starting with observed temperature and salinity and zero velocities, and the quasi-equilibrium solution of an independent integration. For surface dynamical forcing, recently developed normal-year and interannually varying (1958–2000) data sets are used. The model CFC-11 global and basin inventories, particularly in the normal-year forcing case, are below the observed mean estimates, but they remain within the observational error bars. Column inventory spatial distributions indicate nontrivial differences due to both initial condition and forcing changes, particularly in the northern North Atlantic and Southern Ocean. These differences are larger between forcing sensitivity experiments than between the initial condition cases. The comparisons along the A16N and SR3 WOCE sections also show differences between cases. However, comparisons with observations do not clearly favor a particular case, and model–observation differences remain much larger than model–model differences for all simulations. The choice of initial condition does not significantly change the CFC-11 distributions. Both because of locally large differences between normal-year and interannually varying simulations and because the dynamical and CFC-11 forcing calendars are synchronized, we favor using the more realistic interannually varying forcing in future simulations, given the availability of the forcing data sets.

1. Introduction

The chlorofluorocarbons CFC-11 and CFC-12 have been increasingly utilized in evaluating Ocean General Circulation Models (OGCMs), largely due to (i) a good observational data base (the World Ocean Circulation Experiment, WOCE, upon which Global Ocean Data Analysis Project, GLODAP, Key et al. (2004) is largely based), (ii) their well-known atmospheric concentrations, and (iii) because they are inert in the ocean. These tracers are particularly useful in assessing model mixing processes, ventilation rates, deep water formation, and circulation characteristics. A comparison of thirteen OGCMs with regards to their skills in reproducing observed CFC-11 distributions is presented in Dutay et al. (2002). However, the impact of oceanic physical initial conditions (i.e., initial distributions of temperature, salinity, and velocity) and interannually varying surface dynamical forcing (i.e., heat and salt fluxes and wind stress) on the model CFC-11 distributions remains unclear in the Dutay et al. (2002) study: the models in the intercomparison study each use their own unique initial conditions and forcing datasets when the CFC-11 forcing starts. To the best of our knowledge, the question of how the initial conditions affect simulated CFC-11 and CFC-12 distributions has not previously been studied.

The sensitivity of the modeled CFC-11 uptake to surface thermohaline forcing is studied in England and Hirst (1997) where surface temperature and salinity are restored to their climatological seasonal cycles using a relatively short time scale. Considering additional sensitivity experiments that employ even shorter time scales or enhanced salinities or both for restoring during winter months in the high-latitude North Atlantic and Southern Ocean, they conclude that the surface thermohaline forcing plays only a minor role in affecting CFC-11 distributions in contrast with improvements resulting from the inclusion of the Gent and McWilliams (1990) isopycnal transport parameterization instead of a horizontal tracer diffusion formulation. In another study, using a repeat cycle of atmospheric forcing covering 1985–1988 period and enhanced winter-time salinities under sea-ice-covered regions in the Southern Ocean, Doney and Hecht (2002) find that the formulation of surface forcing under sea-ice-covered regions can significantly impact oceanic CFC-11 uptake through an influence on model deep water formation around the Antarctic perimeter.

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In most studies to date, however, the dynamical forcing used in CFC-11 and CFC-12 simulations has been either restoring to climatological annual- or monthly-mean surface temperature and salinity accompanied by climatological annual- or monthly-mean wind stress or applying repeat cycles of observed atmospheric fields covering a specified period (as in Doney and Hecht, 2002) while CFC-11 and CFC-12 surface forcings are constructed to represent the 1938-2000 and 1931–2000 periods, respectively.

In the present study, our goal is to explore and quantify the sensitivity of the oceanic CFC-11 uptake to initial conditions and choice of surface dynamical forcing in an OGCM. We note that our simulations also carry CFC-12 and that we choose to show only CFC-11 distributions here, because the results are nearly identical when CFC-12 is used instead. The initial condition issue is becoming more important as the OGCMs used in climate studies increase their resolution – but still largely remain non-eddy-resolving – and obtaining an equilibrium solution becomes prohibitively expensive. Two popular model initialization choices in the literature are observed temperature and salinity with zero velocities, or a quasi-equilibrium state from another simulation, and it is sensitivity of the solution to these initial conditions that we explore here. For the surface dynamical forcing sensitivity, we consider the recently developed data sets from Large and Yeager (2004, hereafter LY) and use both the interannually varying and normal-year forcing data. These forcing data sets have been recently proposed as common atmospheric forcing data for Coordinated Ocean-ice Reference Experiments (COREs) to investigate the behaviors of global ocean and ocean-sea-ice simulations (Griffies et al., 2009). The present effort is intended to help guide subsequent ocean-model studies that may also choose to use the LY forcing data. We note that the same interannual data set was used in Gent et al. (2006) in their ocean-only CFC-11 simulation. We present brief descriptions of the ocean model and surface forcing as well as a discussion of initial condition differences in Section 2. The results are given in Section 3. Section 4 includes a summary and discussion.

2. Ocean model, surface forcing, and initial conditions

The model is the ocean component of the National Center for Atmospheric Research (NCAR) Community Climate System Model version 3 (CCSM3) and is based on the Parallel Ocean Program of the Los Alamos National Laboratory (Smith and Gent, 2004). In this study, we use the nominal 1° horizontal resolution version of the model. The present model includes the near-surface eddy flux parameterization as implemented by Danabasoglu et al. (2008). Further details of the model set-up and parameterizations, including the eddy diffusivity and viscosity values are given in Danabasoglu et al. (2006) and references therein.

The surface fluxes of heat, salt, and momentum are evaluated using the bulk forcing method described in Large et al. (1997) and LY. We use both the interannually varying (IAF) and the normal-year (NYF) data sets developed by LY. IAF represents a 43-year forcing cycle covering the 1958–2000 period. NYF consists of single annual cycles of all the needed fields constructed from the IAF data to produce similar mean fluxes as the IAF set. The surface CFC-11 and CFC-12 fluxes are calculated for the 1938–2000 and 1931–2000 periods, respectively, following the Ocean Carbon Model Inter-comparison Project (OCMIP-2) protocols (Dutay et al., 2002). However, instead of the protocol specified fields, we use the LY atmospheric data sets in these flux equations.

In the present study, we do not use an active sea-ice model. Instead, we prescribe sea-ice fraction using a daily observed data set from Comiso (1999). This data set uses a bootstrap algorithm data product based on the Nimbus-7 Scanning Multichannel Microwave Radiometer prior to 1988, and the Special Sensor Microwave/Imager from 1988 to 2000. In NYF, the daily sea-ice extent is obtained as an average of the 1978–2000 data. In these sea-ice-covered regions, wind stress passes directly through the sea-ice. The ocean model is allowed to form frazil ice to keep its surface temperature from falling below freezing in regions where there is no observed ice. In such situations, the surface water is heated to the freezing point with a corresponding increase in salt, representing brine rejection due to ice formation. This kind of ice is not transported, and is melted locally before the surface temperature can rise above freezing temperature again. The heat fluxes due to basal ice formation and penetrating short-wave are set to zero, but the freshwater fluxes associated with the former are prescribed as monthly-mean freshwater fluxes diagnosed from an ocean-sea-ice coupled integration. A weak salinity restoring to the Polar Science Center Hydrographic Climatology (PHC2) data (a blending of Levitus et al. (1998) and Steele et al., 2001 data sets) with a 4-year time scale over 50 m is applied globally with its global-mean subtracted. The salinity enhancements along the Antarctic coast described in Doney and Hecht (2002) are included in the restoring data set. A global precipitation correction factor is computed for each year based on the change of the global-mean salinity during that year. This factor is used to multiply the precipitation and runoff fluxes during the next year to partially balance evaporation.

Our first experiment (IAF1) is forced with the IAF data and is initialized using the January-mean temperature and salinity from the PHC2 climatology and zero velocity. IAF1 is integrated for 3 repeat cycles of the IAF data to model year 129, i.e., the end of calendar year 2000. The CFC-12 and CFC-11 surface fluxes are introduced in model years 60 and 67, respectively. These model years correspond to calendar years 1974 and 1981, respectively, for the surface fluxes of heat, salt, and momentum in the IAF data cycle, while they correspond to calendar year 1931 for CFC-12 and calendar year 1938 for CFC-11 surface fluxes. Therefore, the calendar years for the atmospheric data used in all surface flux calculations are identical, i.e., synchronous, only during the third cycle of the IAF data, corresponding to calendar years 1958–2000. In other words, only during this integration segment the surface fluxes of heat, salt, momentum, CFC-11, and CFC-12 follow the same calendar years. The second experiment (IAF2) is forced identically with the IAF data, but is initialized from the end state of a 441-year independent simulation with NYF. We note that surface and intermediate waters are in quasi-equilibrium after 441 years, but most deep waters certainly are not. IAF2 is a 70-year integration to the end of calendar year 2000 in which the CFC-11 and CFC-12 are introduced right from the beginning in years 1 and 8, respectively. Here, the first model year corresponds to 1974 in the IAF data cycle for the heat, salt, and momentum fluxes and to 1931 for the CFC-12 surface fluxes. Thus, as in IAF1, all surface fluxes in IAF2 follow the same calendar years for the atmospheric data only during the last 43 years of integration, corresponding to calendar years 1958–2000. Finally, experiment NYF2 is identical to IAF2, except that it is forced with the NYF data. In each experiment, the initial CFC-11 and CFC-12 concentrations are set to zero.

The initial conditions considered here represent reasonable and practical choices, typical of those adopted in ocean modeling community. To show a measure of the initial condition differences before the CFC-11 surface fluxes are introduced, we present the annual- and zonal-mean potential density difference distributions obtained by subtracting model year 60 of IAF1 from model year 1 of IAF2 in Fig. 1a and b for the Atlantic + Arctic and Pacific + Southern Ocean basins, respectively. This figure reveals that IAF2 generally has lighter waters in the upper ocean and denser waters in the deeper ocean, relative to IAF1. The largest differences are in excess of 0.5 kg m^{-3}, occurring in the near-surface Arctic Ocean. In the North Atlantic, the differences reach 0.3 kg m^{-3} near the surface. The Antarctic Intermediate Water densities in IAF2 are lighter by