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Effects of sinking of salt rejected during formation of sea ice on results of an ocean-atmosphere-sea ice climate model

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Abstract. We show that results of an ocean-atmosphere-sea-ice model are sensitive to the treatment of salt rejected during formation of sea ice. In our Control simulation, we place all rejected salt in the top ocean-model level. In the Plume simulation, we instantaneously mix rejected salt into the subsurface ocean, to a maximum depth which depends on local density gradients. This mimics the effects of subgrid-scale convection of rejected salt. The results of the Plume simulation are more realistic than those of the Control simulation: the spatial pattern of simulated salinities (especially in the Southern Ocean), deep-ocean temperatures, simulated sea-ice extents and surface air temperatures all agree better with observations. A similar pair of simulations using horizontal tracer diffusion instead of the Gent-McWilliams eddy parameterization show similar changes due to instantaneous mixing of rejected salt.

Introduction

An inability to realistically simulate Southern Ocean tracers is a common problem in ocean-climate models. This problem is due in part to excessive Southern Ocean convection (Hirst and McDougall, 1996). The Gent-McWilliams ("GM90") eddy parameterization (Gent and McWilliams, 1990) dramatically reduces Southern Ocean convection (Danabasoglu and McWilliams, 1995) and improves simulated CFC uptake (e.g. England and Hirst 1997, Robitaille and Weaver, 1996); however, especially in simulations using ocean-sea ice models, the remaining convection may still be excessive.

Duffy and Caldeira 1997 and Caldeira and Duffy, 1998 (hereafter referred to as D&C/C&D) showed that excessive simulated convection in the Southern Ocean can be eliminated by more careful treatment of salt rejected during formation of sea ice. In their "Test" simulation, rejected salt was spread uniformly between the ocean surface and a depth of 160 m. This resulted in much more realistic simulated salinities and uptake of CFC-11, compared to a Control simulation in which all rejected salt was placed in the top model level.

Instantaneous mixing of rejected salt into the subsurface ocean in models is physically motivated. Brine-induced convection occurs in the real ocean on horizontal spatial scales which are much smaller than a typical GCM grid cell. Thus traditional convective parameterizations, which mix entire grid cells, poorly approximate this process. Because of this disparity in spatial scales, and because it mixes rejected salt more efficiently than other tracers, brine-induced convection is better representation by vertically mixing only rejected salt than by grid-scale convection.

Here we expand on the results of D&C/C&D in several ways. First, unlike that used by D&C/C&D, our model includes a simplified representation of the atmosphere. This allows us to model atmosphere-related feedbacks, and eliminates artifacts that may arise from surface boundary conditions in ocean-only models. Second, we use a more realistic formulation of mixing of salt rejected during sea ice formation. Whereas D&C/C&D mixed rejected salt down to a uniform maximum depth (160 m), in our "plume" simulations the maximum depth of mixing is calculated based on a prescribed density contrast relative to the surface. This has the realistic property that rejected salt is mixed more deeply in regions where vertical density stratification is weak, and vice-versa. Third, whereas D&C looked at effects of sinking of rejected salt only on simulated salinities, here we discuss effects on temperatures as well. Finally, the model we use here is different from that used by D&C/C&D; thus we provide independent confirmation of their results.

We present four simulations which test sensitivity to instantaneous mixing of rejected salt. The first pair, Control and Plume, use the GM90 eddy parameterization and no background horizontal mixing of tracers. The second pair, ControlHOR and PlumeHOR, use horizontal mixing of tracers.

Model Description

The simulations presented use the University of Victoria ("UVic") global ocean-atmosphere-sea ice model. The ocean component of this model is based on the GFDL MOM version 2 (Pacanowski et al., 1995). Each grid cell is 3.6 degrees in longitude by 1.8 degrees in latitude. We use a maximum of 19 vertical levels. The topography is realistic. Vertical mixing coefficients of 0.6 cm^2/s (tracers) and 20 cm^2/s (momentum) are prescribed. Surface momentum fluxes are prescribed, from monthly NCEP reanalyses. The sea ice component of our model treats dynamics (Hibler, 1979) and thermodynamics (Hunke and Dukowicz 1997). The atmospheric component is an updated version of the vertically integrated energy-moisture balance model of Fanning and Weaver (1996). The model diffusively transports heat and moisture on the same latitude-longitude grid as the ocean. Precipitation occurs when relative humidity exceeds 85%. No "flux adjustments" or restoring of temperatures or salinities are employed.

The four simulations presented here differ in their treatment of salt rejected when sea ice forms, and of lateral mixing of ocean tracers. The Control and Plume simulations use the GM90 eddy parameterization; thickness and isopycnal diffusivities are both 2e07 cm^2/s, and mixing surfaces are limited to a maximum slope of 0.01. The ControlHOR and PlumeHOR simulations use horizontal mixing of tracers, with

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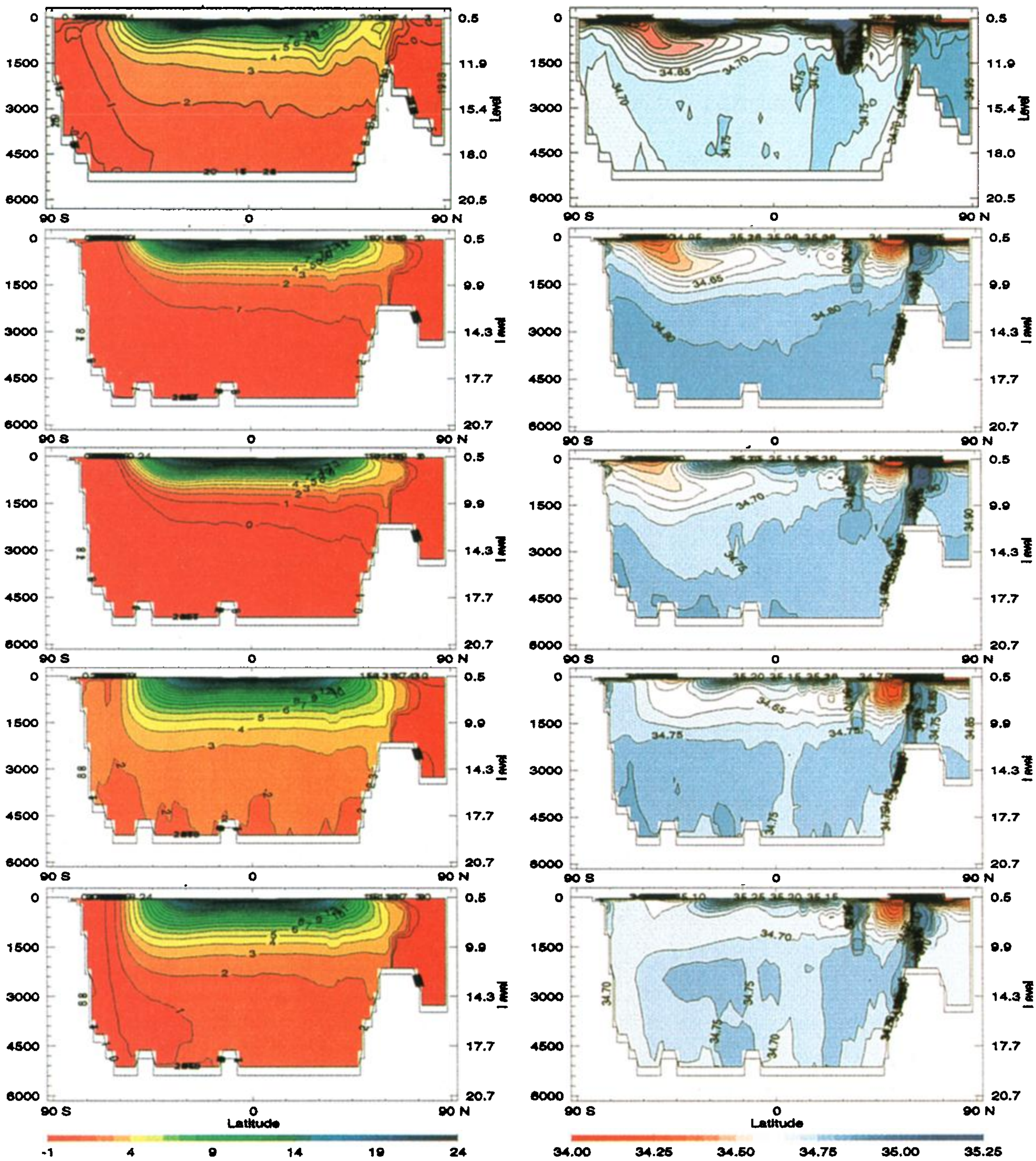

Figure 1: Latitude-depth sections of temperature (left) and salinity (right), from (top to bottom) observations (Levitus and Boyer, 1994), the Control, Plume, ControlHOR and PlumeHOR simulations. All data are annual means, averaged in longitude over the world ocean.

a diffusivity of 2e07 cm^2/s. In the Control and ControlHOR simulations, all rejected salt is placed in the top ocean model level. In the Plume and PlumeHOR simulations, rejected salt is spread uniformly between the surface whatever depth has a potential density 0.4 kg/m^3 greater than the surface (or the ocean bottom, whichever is shallower). The density contrast of 0.4 kg/m^3 was chosen because it produces realistic salinities, and because it yields maximum mixing depths which are similar to typical mixed-layer depths. In all simulations meltwater produced by melting sea ice is placed entirely in the top ocean model level. All simulations were initialized from the final state of a 5000-year "spinup" of the UVic coupled model, and were then run for another 1000 simulated years.

Results

Instantaneous mixing of rejected salt into the subsurface ocean has significant effects on the model results. The spatial pattern of simulated salinities in the Southern Ocean is closer to observations in the Plume run than in the Control run (Figure 1). In the Control run, the prominent salinity minimum

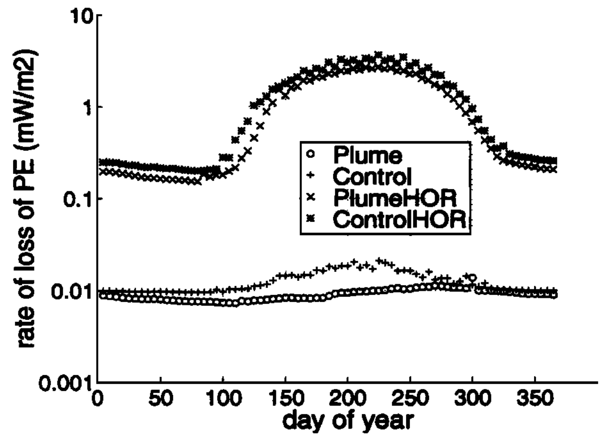

Figure 2: Spatially-averaged rate of loss of potential energy (mW/m^2) from convective adjustment, as a function of time of year, in the Control, Plume, ControlHOR and PlumeHOR simulations. Spatial averages are performed over the full ocean depth and over all area south of longitude -50 deg.

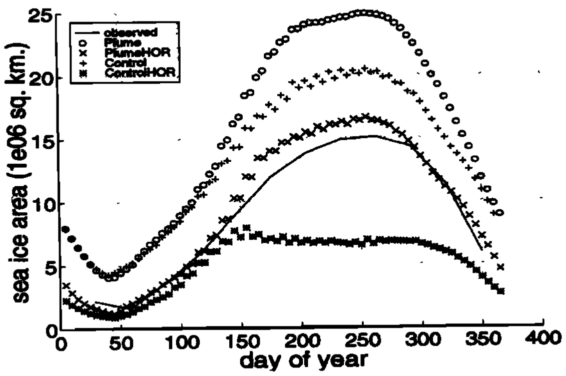

Figure 3: Southern hemisphere sea ice area (million km^2) as a function of time of year, in the Control, Plume, ControlHOR, and PlumeHOR simulations, and from passive microwave observations (Gloersen et al., 1992).

associated with Antarctic Intermediate Water (AAIW) is too weak; it is more pronounced in the Plume run. In this run, the salinity contrast between AAIW and the deep Southern Ocean is approximately correct, but both locations are too salty by about 0.1 PSU. The AAIW salinity minimum is too weak in the Control simulation because excessive convection in the Southern Ocean tends to erase vertical salinity gradients. The reduction in Southern Ocean convection in the Plume simulation (Figure 2) thus allows a more realistic spatial pattern of salinity in this region. A similar improvement in salinity is seen in the PlumeHOR simulation relative to the ControlHOR simulation (Figure 1). However, in both these simulations salinities are much less realistic than in the comparable simulations using GM90. The reason involves horizontal diffusion of tracers in the Southern Ocean. At depths of about a kilometer, horizontal diffusion tends to bring warm, fresh (i.e. light) water southwards towards Antarctica. This results in weak stratification and excessive convective activity (Figure 2). This excessive convection wipes out vertical salinity gradients and prevents a realistic representation of the salinity minimum associated with AAIW.

Deep-ocean temperatures in the Control run are too cold (Figure 1). Ocean-only simulations which use GM90 often have the same problem (e.g. Danabasoglu and McWilliams, 1995; Duffy et al. 1997). As Figure 1 suggests, the problem originates largely in the Southern Ocean (i.e. this is where the needed heat escapes the model ocean). Excessive under-ice convection cools the deep ocean in two ways. First, by bringing relatively warm water to the surface, under-ice convection reduces Antarctic ice cover and increases heat fluxes to the atmosphere. Second, convection increases the rate of vertical heat transport within the ocean. Temperatures in the

Table 1. Comparison of Model Results and Observations. "South. Oc." averages are horizontal means taken over latitudes -90 to -50. All values are annual means.

	Obs	Cont	Plume	CntrlHOR	PlumeHOR
glob. ocean temp.	3.84	2.45	3.389	4.528	5.422
South. Oc. SST	2.38	3.06	2.88	3.965	3.502
South. Oc. SSS	33.9	34.1	33.88	34.578	34.336
South. Oc. SAT	–	-8.24	-8.65	-5.199	-6.70

Plume run (which has less convection than the Control run) are therefore closer to observed, although they are still too cold in the global mean (Table 1). The warming of the deep ocean due to mixing of rejected salt is a robust result, for reasons just described; by contrast, the values of deep ocean temperatures relative to Levitus can be adjusted by model "tuning". For example, deep ocean temperatures in the ControlHOR are relatively realistic (Figure 1), in part due to careful adjustment of model parameters (especially planetary albedos). The PlumeHOR simulation is warmer than both the ControlHOR simulation and the Levitus climatology.

The effects of sinking of rejected salt on sea-surface temperatures (SSTs) and salinities (SSSs) are largely confined to the Southern Ocean. Here, SSTs in the Plume simulation are generally colder than in the Control simulation, due to reduced convection. Agreement with the Levitus climatology is on the whole improved (Table 1). Instantaneous mixing of rejected salt reduces SSSs in the Southern Ocean, because salt that would otherwise be placed in the top model level is put into the subsurface ocean. As a result, the surface of the Southern Ocean, which was too salty in the Control simulation, is slightly too fresh in the Plume simulation.

Instantaneous placement of rejected salt into the subsurface ocean increases the sea ice coverage near Antarctica, in both pairs of simulations (Figure 3). This occurs because placing all rejected salt in the top model level produces excessive grid-scale convection, which brings up relatively warm water and tends to melt ice (Martinson 1990).

Sinking of rejected salt has much less effect on the simulated atmosphere than on the ocean or sea ice. Again, differences between the Control and Plume simulations are largely confined to the region over the Southern Ocean. Surface air temperatures in the Southern Ocean region are colder in the Plume simulation than in the Control simulation (Table 1). This is attributable to reduced oceanic convection and increased sea ice cover in the Plume simulation, both of which reduce fluxes of heat from ocean to atmosphere.

Discussion and Conclusions

Our results differ from previous results in several respects. First, instantaneous mixing of rejected salt has less effect on simulated salinities and convection in the runs presented here than in those of D&C/C&D. This difference occurs for at least two reasons. First, the runs presented here have less Antarctic sea ice volume than those of D&C/C&D; thus any effects of mixing rejected salt are bound to be smaller. Second, in the simulations of D&C/C&D, global mean salinities drift while the model solution is approaching a steady state. Thus, in these simulations, mixing rejected salt changes the global mean salinity as well as the spatial pattern of salinity. This makes the effect of sinking rejected salt appear more striking. By contrast, in the UVic coupled model, which uses no flux adjustments or salinity restoring, time-and space-averaged surface fluxes of fresh water are very nearly zero. Therefore the global mean ocean salinity remains very close to its initial (observed) value. Thus mixing rejected salt can improve the spatial pattern of salinity, but the global mean is unaffected.

Mixing of rejected salt into the subsurface ocean is a simplified representation of subgrid scale convection. Results similar to those we obtain via mixing of rejected salt might be obtained by applying the K-Profile Parameterization ("KPP"; Large et al., 1994) or similar parameterization of vertical mixing, on horizontal scales smaller than a GCM grid cell. For example, one could apply KPP separately in the ice-covered and ice-free parts of each grid cell.

We have tested a simple representation of subgrid scale convection due to brine rejection, in which we instantaneously mix rejected salt into the subsurface ocean. In two simulations using the GM90 eddy parameterization, instantaneous mixing of rejected salt has significant improving effects on the steady-state climatology of an ocean-atmosphere-sea ice climate model: convective activity is reduced, deep-ocean temperatures are closer to observations, salinities and sea ice coverage are more realistic. Salinity improvements are mainly in the representation of the salinity minimum associated with Antarctic Intermediate Water.

A comparable pair of simulations using horizontal mixing of tracers instead of GM90 show similar effects of sinking rejected salt; however, both simulations which use horizontal mixing have less realistic salinities than either of our GM90 simulations, because of unrealistically strong Southern Ocean convection. Thus, GM90 dramatically reduces Southern Ocean convection and, in the runs presented here, results in much more realistic Southern Ocean salinities. Instantaneous mixing of rejected salt into the subsurface ocean further reduces Southern Ocean convection and further improves simulated salinities and other aspects of the model solution.

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