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Sensitivity of simulated salinities in a three-dimensional ocean general circulation model to vertical mixing of destabilizing surface fluxes

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Abstract We present simulations performed with a three dimensional global ocean general circulation model which show that simulated salinities and amounts of convective mixing are very sensitive to vertical mixing of surface buoyancy fluxes. If, as usual, surface buoyancy fluxes are placed entirely in the topmost model level, our model produces excessive convective mixing in the Southern Ocean. This results in poor stimulated salinity in the Southern Ocean. In this simulation, we assume, as usual, that both surface buoyancy forcing and vertical mixing are homogeneous within each grid cell. If, on the other hand, destabilizing surface fluxes are instantaneously mixed into the subsurface ocean, the model produces much less convective mixing and much more realistic salinities. The vertical mixing of surface buoyancy fluxes performed in this simulation is equivalent to assuming that those fluxes affect only a small fraction of each grid cell, and cause vertical mixing only in that limited area. Our interpretation of these results is that the usual assumption that both surface buoyancy forcing and vertical mixing are uniform within each grid cell has a detrimental effect on model results; these results could be significantly improved by good parametrizations which treat the horizontal inhomogeneity of surface buoyancy forcing and of vertical mixing.

1 Introduction

It has been known for some time that ocean general circulation models often produce excessive convective mixing in the Southern Ocean. In simulations of ocean uptake of transient tracers (e.g., CFCs), this excessive mixing results in excessive CFC uptake in the Southern ocean (e.g., some simulations in England and Hirst 1997). Excessive grid-scale convection in the simulated Southern Ocean also typically results in poor simulated salinities in the deep Southern Ocean. This occurs because strong convection results in overly rapid communication between the surface and deep oceans. If the surface salinity values are held close to observed values (such as by a "restoring" boundary condition) then the simulated deep Southern Ocean tends to take on the salinity values of the surface ocean, and is fresher than observed.

In two recent papers (Duffy and Caldeira 1997; Caldeira and Duffy 1998; hereafter D&C/C&D) we showed that excessive grid-scale convection in the simulated Southern Ocean can be eliminated by more careful treatment of surface fluxes, specifically of salt rejected during the formation of sea ice. We performed two simulations using a 3-dimensional ocean GCM coupled to a dynamic/thermodynamic sea ice model. In our "control" simulation, salt rejected during formation of sea ice was, as usual, placed in the top model level (25 m thick) and we relied upon the normal model transport processes to move rejected salt into the rest of the ocean. The density instabilities created by the introduction of rejected salt into the 25-m thick surface level resulted in excessive convective mixing in the Southern Ocean; this resulted in the deep Southern Ocean being too fresh. In addition, simulated column inventories of CFCs in the Southern Ocean were much too high. The overly fresh deep Southern Ocean, and the excessive uptake of transient tracers in the Southern Ocean are both typical results of global ocean circulation models.

In the D&C/C&D "test" simulation, salt rejected during formation of sea ice, instead of being placed entirely in the 25-m thick surface level, was spread uniformly between the ocean surface and a maximum depth of 160 m. Otherwise, this simulation was identical to the control simulation. This instantaneous

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mixing of rejected salt tested the hypothesis that convective adjustment in GCMs, which operates only on the scale of entire grid cells (typically hundreds of kilometers), cannot adequately represent convective mixing of rejected salt, which typically occurs on much smaller horizontal spatial scales (hundreds of meters; Denbo and Skyllingstad 1996, and references therein). Thus our instantaneous mixing of rejected salt had an effect similar to that of a (hypothetical) simple parametrization of sub-grid scale convection. The situation we were mimicking is one where rejected salt is mixed down to the bottom of the mixed layer in horizontal regions which are very small compared to the entire grid cell. Thus only the ice-rejected salt, not heat or other salt, was mixed. The maximum depth (160 m) of mixing of rejected salt was chosen arbitrarily, in order to completely eliminate the problem of the deep ocean being too fresh. However, this depth is physically reasonable in that it is typical of mixed layer depths (Levitus 1982; Visbeck et al. 1995; Martinson 1990). This "test" simulation resulted in dramatically improved simulated salinities and much more realistic simulated uptake of a transient tracer (CFC) compared to results of the control simulation described above. In addition, the strength of the Antarctic Circumpolar Current was more realistic than in the control simulation.

The primary reason for these improvements is that spreading rejected salt over a vertical thickness of 160 m resulted in much less density instability and therefore much less convective mixing than occurred in the control simulation, where all the rejected salt was placed in the 25-m thick surface level. Our interpretation of these results is that the model's convective adjustment parametrization, which operates only on the scale of entire grid cells, is too clumsy to adequately represent convection triggered by salt rejection, which occurs on horizontal spatial scales much smaller than a typical GCM grid cell. Instantaneously mixing rejected salt down to 160 m, without changing the other tracers in the grid cell, in effect simulates vertical mixing of rejected salt in a tiny fraction of each grid cell (i.e., mimics subgrid scale convection).

Although these results demonstrate an interesting sensitivity in the model, they have several significant limitations. The first is that sinking rejected salt to a uniform and time-invariant maximum depth (160 m) is not an adequate parametrization of subgrid scale convection. In reality, the maximum depth of small-scale convective mixing depends on local conditions and forcings. Second, the "test" simulation of D&C/C&D does not treat salinity and temperature in a consistent manner. Subgrid scale convection can be caused thermal, as well as saline, forcing; this was not represented in the test simulation of D&C/C&D. Third, subgrid scale convection occurs in regions of the ocean which are not covered by sea ice.

In this study we present new simulations which further explore then sensitivity of model results to vertical mixing of surface fluxes and which attempt to address some of the limitations in the simulations of D&C/C&D. The first is a "control2" simulation, in which all surface fluxes are, as usual, placed entirely in top model level. In this simulation, both surface buoyancy forcing and the vertical mixing which result from that forcing are, again as usual, assumed to be homogeneous within each model grid cell. Like others, this simulation produces an overly fresh deep ocean.

The second new simulation is a "test2" simulation, which assesses the sensitivity of model results to a more general vertical mixing of surface fluxes than was done by D&C/C&D. Whereas D&C/C&D experimented with mixing of only salt rejected during sea ice formation, the test2 simulation mixes destabilizing fluxes of heat and fresh water, in all regions of the ocean, in a manner described in detail later. Thus, this simulation, unlike the test simulation, treats temperature and salinity in a consistent manner. Finally, the test2 simulation improves on the D&C/C&D test simulation by calculating the maximum depth of subgrid scale vertical mixing based on local conditions, rather than using a prescribed, constant maximum depth of vertical mixing. By vertically mixing surface fluxes while leaving the remaining contents of each grid cell unchanged, this simulation makes the assumption that surface buoyancy forcing and the resulting vertical mixing occur in a tiny fraction of each grid cell.

The test2 simulation is identical to the control2 simulation, except for the handling of surface fluxes of heat and salinity. In the test2 simulation, surface fluxes which tend to be destabilizing (addition of salt or loss of heat) in general affect not just the surface level, but can be instantaneously mixed into subsurface levels, depending on local densities. The maximum depth of mixing is determined by a specified contrast in potential density with respect to the surface. That is, destabilizing fluxes are spread uniformly between the surface and whatever depth is 0.2 kg/m^3 denser than the ocean surface. This depth is calculated by interpolating between potential densities calculated at each model level. If no depth has a density as high as 0.2 kg/m^3 denser than the surface level, as sometimes occurs in shallow regions, fluxes are mixed down to the ocean bottom. Conversely, if interpolation indicates that the depth which is 0.2 kg/m^3 denser than the ocean surface level lies within the surface level, then all fluxes are placed in the surface level. This way of calculating the maximum depth of mixing has the realistic characteristic that the mixing is deeper in regions of weak vertical density stratification than in regions of strong stratification; in addition, the maximum depth of mixing can change if the ocean density structure changes.

In the test2 simulation we mix vertically surface fluxes which tend to be destabilizing; i.e., we mix heat fluxes which remove heat from the ocean, and salt fluxes which add salt to the ocean. This is done whether the combined (heat plus salt) surface flux increases or decreases the surface density. The rationale for treating the two types of fluxes separately is that surface fluxes are often highly heterogeneous on the scale of a GCM grid cell. For example, a large heat loss through a lead in sea ice can cause convection beneath that lead; at the same time, the combined heat plus fresh water flux, *averaged over a region the size of a GCM grid cell*, may act to decrease density (i.e., may be stabilizing).

2 Model description

The simulations presented here were performed with the LLNL three-dimensional ocean general circulation model. This model is based on the GFDL MOM version 1.1 (Pacanowski et al. 1991), but has significant scientific, numerical, and computational enhancements relative to that model. For the simulations presented here each grid cell has a size of 4° of longitude by 2° of latitude. There are a maximum of 23 vertical levels. The model bathymetry is essentially realistic (consistent with the model resolution).

Coefficients of vertical mixing of tracers are prescribed, as by Hirst and McDougall (1996). Between the top two model levels the mixing coefficient is 1.0 cm^2/s, to represent the surface mixed layer. Below this, vertical diffusion coefficients vary from 0.2 cm^2/s near the surface to 1.5 cm^2/s at the ocean bottom. We use the "Gent-McWilliams" parametrization (Gent and McWilliams 1990) to represent the effects of subgrid scale eddies on lateral transport of tracers. Isopycnal and thickness diffusivities are 2.0e07 and 1.0e07 cm^2/s, respectively. Following Robitaille and Weaver (1995), we use a latitude-dependent horizontal viscosity which increases with the cosine of latitude from 1e09 cm^2/s at the poles to 6e09 cm^2/s at the equator. The higher viscosity at the equator is intended to minimize Peclet-type instabilities associated with high vertical velocities (Weaver and Sarachick 1990; Duffy et al. 1997). To further minimize these problems, within 30° of the equator, we increase vertical diffusivities and vertical viscosities as needed to ensure that neither of the grid-Peclet stability conditions given by Weaver and Sarachick (1990) are violated.

Surface fluxes of momentum are prescribed, and are obtained by interpolating between monthly-mean wind stresses of Hellerman and Rosenstein (1983). Surface fluxes of fresh water are handled as equivalent salt fluxes. Surface fluxes of heat and salt are calculated by restoring to the Levitus and Boyer (1994) observed monthly temperature and salinity values, with restoring time constants of 50 days for both temperature and salinity. As described earlier, in the test2 simulation, fluxes which tend to be destabilizing are in general instantaneously mixed into the subsurface ocean. We do not use a sea-ice model in the runs presented here. Thus, surface fluxes of fresh water due to freezing and melting of sea ice are not treated explicitly; rather, these fluxes are represented implicitly via the restoring boundary condition.

Both simulations presented here were initialized from observed climatological temperatures and salinities (Levitus and Boyer 1994). Initial velocities were zero. As discussed by Bryan (1984), both simulations here used longer time steps in the deep ocean, to speed the solutions' approaches to steady states. Both simulations were run for 1190 simulated surface years, equivalent to 8932 simulated years in the deepest model level. After this "spinup", both simulations were run for 27 simulated years with no deep-ocean acceleration, to minimize distortions to the seasonal cycle (Danabasoglu 1996). Results presented late are annual means from the end of this 27-year period.

3 Results

3.1 Simulated salinities

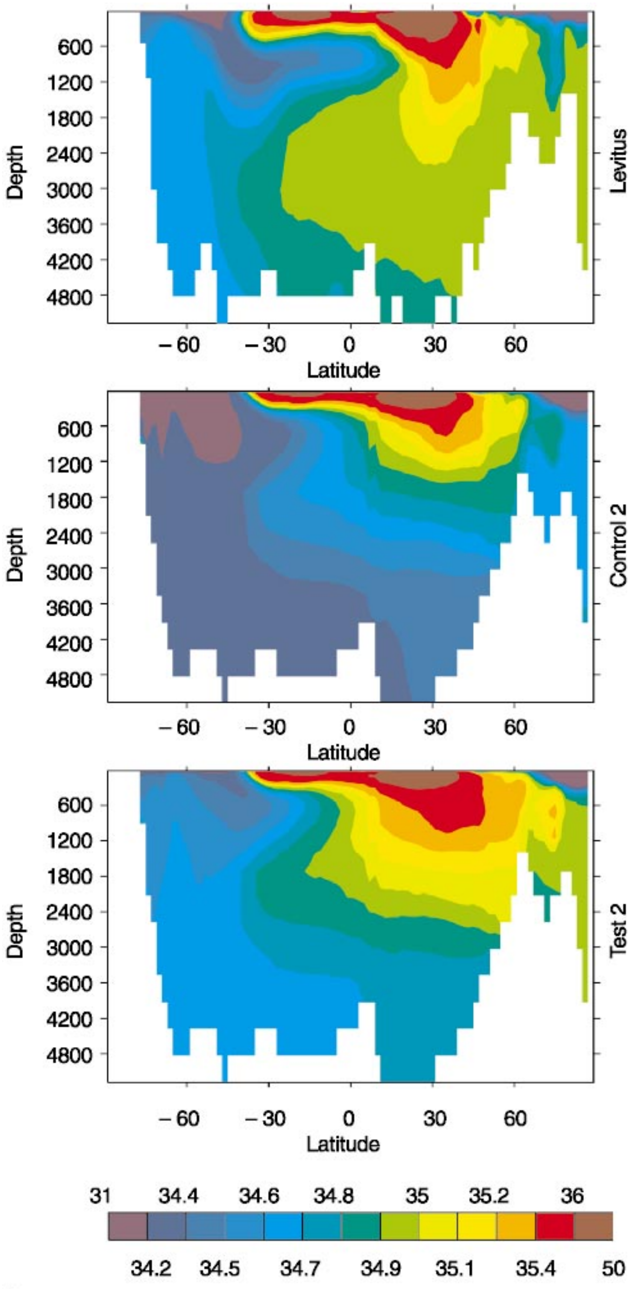
Simulated salinities in the control2 run are unrealistic. In both the Atlantic and Indo-Pacific basins, the deep ocean is much too fresh (Figs. 1 and 2); these results are typical of global ocean models. By contrast, salinities in the test2 simulation are much more realistic. The problem of the deep ocean being too fresh is eliminated completely in the Indo-Pacific Ocean and almost completely in the Atlantic. The main reason for the improvement is a dramatic reduction in grid-scale convection in the Southern Ocean in the test2 simulation compared to the control2 simulation (Fig. 3). This reduction occurs because the instantaneous vertical mixing of destabilizing surface fluxes in the test2 simulation reduces the tendency for surface fluxes to cause density instabilities and grid-scale convection. Figure 4 shows that these fluxes are mixed to depths which are often within the 25 m thick surface level, except in the Southern and North Atlantic Oceans, where maximum mixing depths can be several hundred meters.

3.2 Simulated temperatures

Simulated temperatures in the Test2 simulation are very similar to those in the control2 simulation, in both the Atlantic and Indo-Pacific Oceans (Figs. 5 and 6). This is in sharp contrast to the results for salinity, which are very different in the two simulations. Why the (non)-difference? The principal change in ocean circulation caused by mixing of surface fluxes is the reduction in Southern Ocean convection discussed above. Overturning stream functions, for example, are quite similar in the test2 and control2 simulations (Fig. 7). This reduction in grid-scale covection has a big effect on simulated salinities, because these should have strong vertical gradients, at least in the upper ocean. Overly strong convection can wipe out these gradients, producing simulated salinities which are nearly homogeneous vertically, and therefore unrealistic. By contrast, temperatures in the Southern Ocean *should* have weak vertical gradients; isotherms in this region are more nearly vertical. Thus overly strong convection has relatively little effect on simulated temperatures, which are already relatively homogeneous in the vertical direction.

3.3 Surface fluxes

It is important to evaluate the effect of vertical mixing of surface fluxes on the magnitude of those fluxes, because it is important to know if we are producing more realistic simulated salinity distributions by means



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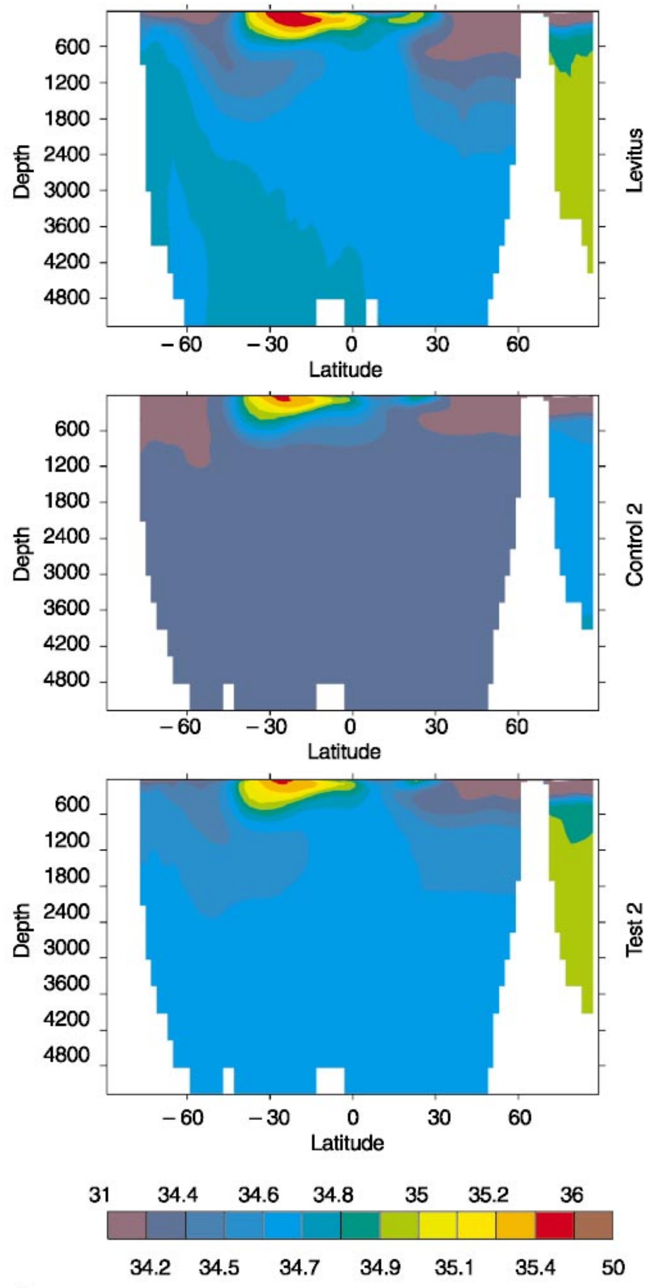

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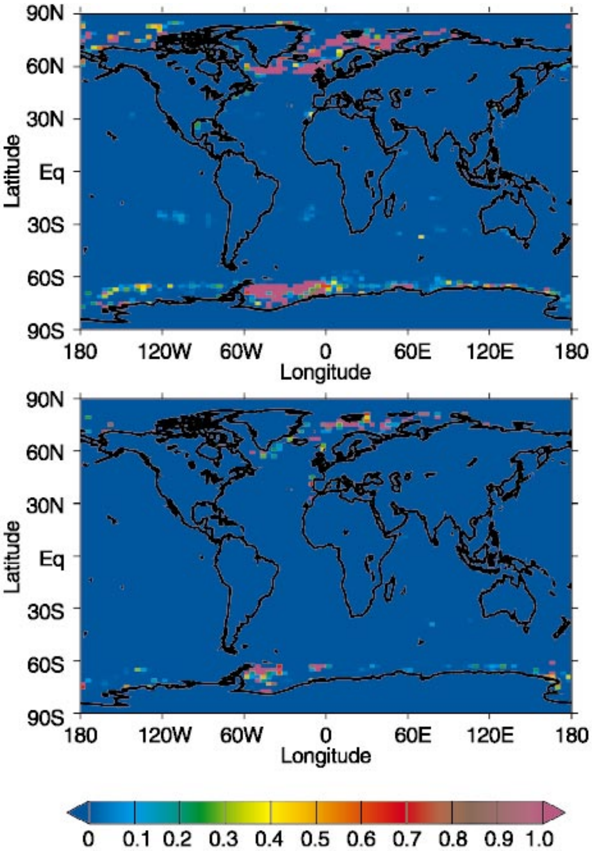
Fig. 1 Latitude-depth sections of salinity in the Atlantic Ocean, from observations (Levitus and Boyer 1994, *top panel*), and as simulated in the control2 and test2 simulations (*middle* and *bottom panels*, respectively). All data shown are annual means, and are averaged in longitude over the Atlantic basin. Salinities in the control2 simulation are unrealistic, in that the deep ocean is much too fresh. The test2 simulation has much more realistic salinities

Fig. 2 Same as Fig. 1, except for the Indo-Pacific Ocean. Again, the deep ocean is much too fresh in the control2 simulation, and this problem is eliminated in the test2 simulation

of unrealistic surface fluxes of salt. (As discussed already, the simulations presented here use equivalent salt fluxes instead of freshwater fluxes.) In particular, we want to avoid eliminating the problem of the overly fresh deep ocean by adding unrealistically large amounts of salt to (i.e., subtracting unrealistically large amounts of fresh water from) the North Atlantic or Southern Ocean. As Fig. 8 shows, however, this is not happening. Surface fluxes of fresh water are very similar in the test2 and control2 simulations, and slightly *less* fresh water is being removed from the Southern Ocean in the test2 simulation compared to the control2



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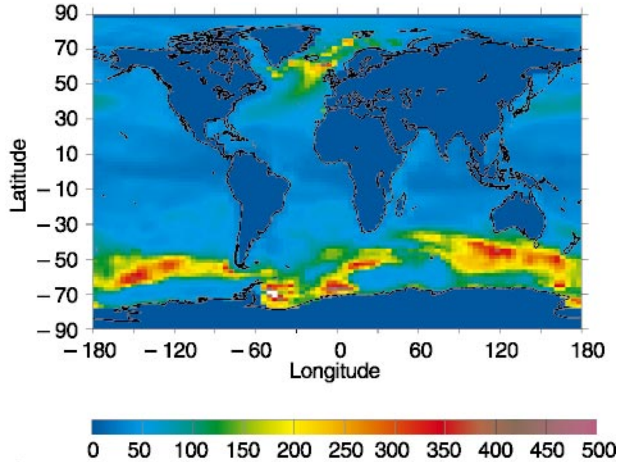

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Fig. 3 Vertically-integrated Potential energy released by convective adjustment, as a function of latitude and longitude, in the control2 (top panel) and test2 (bottom panel) simulations. In the Southern and North Atlantic Oceans the test2 simulation has much less convective activity than the control2 simulation. This reduction occurs because in the test2 simulation destabilizing surface fluxes are mixed instantaneously into the subsurface ocean; this reduces the tendency to create density instabilities and to cause convection. Units are 10^{-4} w/m^2

Fig. 4 Maximum depths of mixing of surface fluxes in the test2 simulation. In this simulation, surface fluxes which tend to be destabilizing (additions of salt or losses of heat) are instantaneously mixed into the subsurface ocean. The maximum depth of this mixing is calculated based on the prescribed density contrast (0.2 kg/m^3) with respect to the surface. This figure shows that maximum depth in meters, in an annual mean

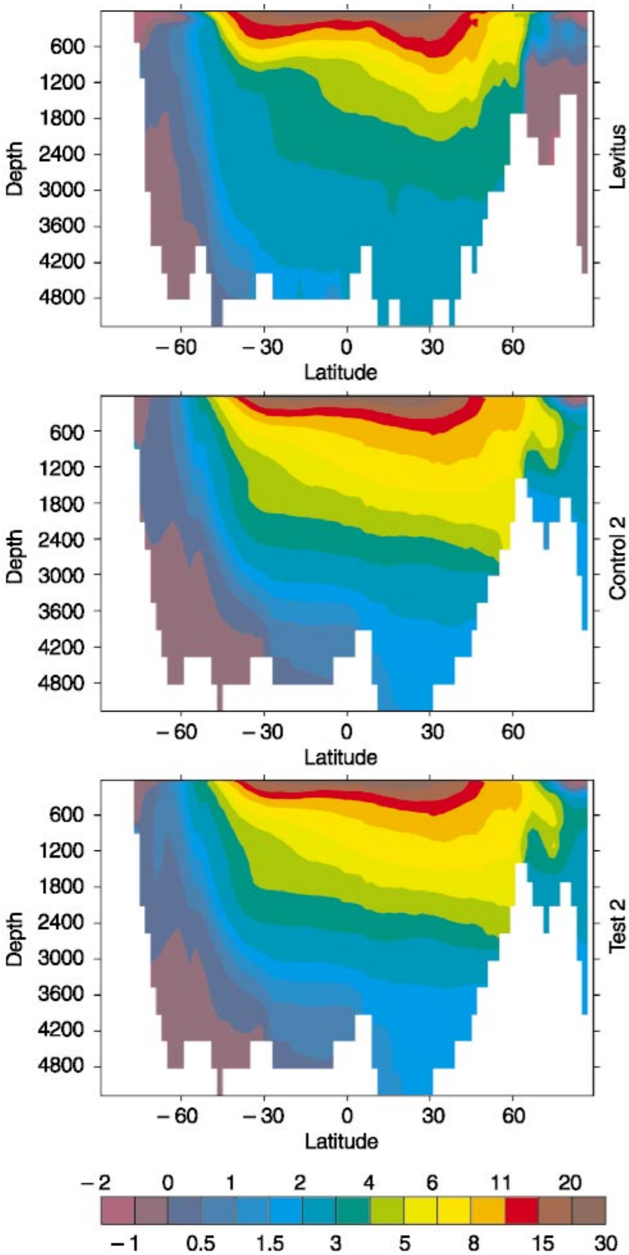
simulation. Thus the improved salinities in the test2 simulation are obtained via more realistic ocean circulation rather than via altered surface fluxes.

4 Discussion

The mixing of surface fluxes done in our test2 simulation (and in the D&C/C&D test simulation) differs from mixing done by parametrizations of vertical mixing, such as "KPP" (Large et al. 1994), which are usually applied to entire grid cells. We are mixing only surface fluxes, leaving temperatures and salinities in the grid cells in question otherwise unchanged. This mimics a situation in which heterogeneous surface buoyancy forcing causes vertical mixing in a tiny (effectively infinitesimal) fraction of a GCM grid cell. By contrast, KPP and similar mixing parametrizations calculate coefficients of vertical diffusivity; these coefficients are then (typically, although not necessarily) used to mix the entire contents of vertically adjacent grid cells. This treats individual grid cells as homogeneous regions, and does not attempt to represent the heterogeneity of surface forcing or of vertical mixing.

The two simulations we present here represent two contrasting extreme assumptions about the horizontal heterogeneity of surface buoyancy forcing and of the resulting vertical mixing. The control2 simulation assumes, as do most ocean model simulations, that both the surface buoyancy forcing and the resulting vertical mixing are completely homogeneous within each model grid cell. The test2 simulation makes the contrasting assumption that surface buoyancy forcing and resulting mixing occur in a tiny fraction of each grid cell. Reality, of course, lies somewhere between these two extremes. The fact that the two assumptions give very different results, however, indicates that models would benefit from the ability to treat the subgrid scale heterogeneity of surface buoyancy forcing and of vertical mixing.

We know of only one convection parametrization (Paluszkiewicz and Romea 1996) which does attempt to represent the horizontal inhomogeneity of vertical mixing. (It does not, however, attempt to represent subgrid scale heterogeneity of surface buoyancy forcing.) This parametrization has not yet been tested in a coarse-resolution, global ocean model (T. Paluszkiewicz, private communication). While it would certainly be useful to make such tests, it is also useful to perform sensitivity studies such as those presented here, which can provide useful insights into the behavior of the model, and can demonstrate the potential benefits of improved parametrizations.



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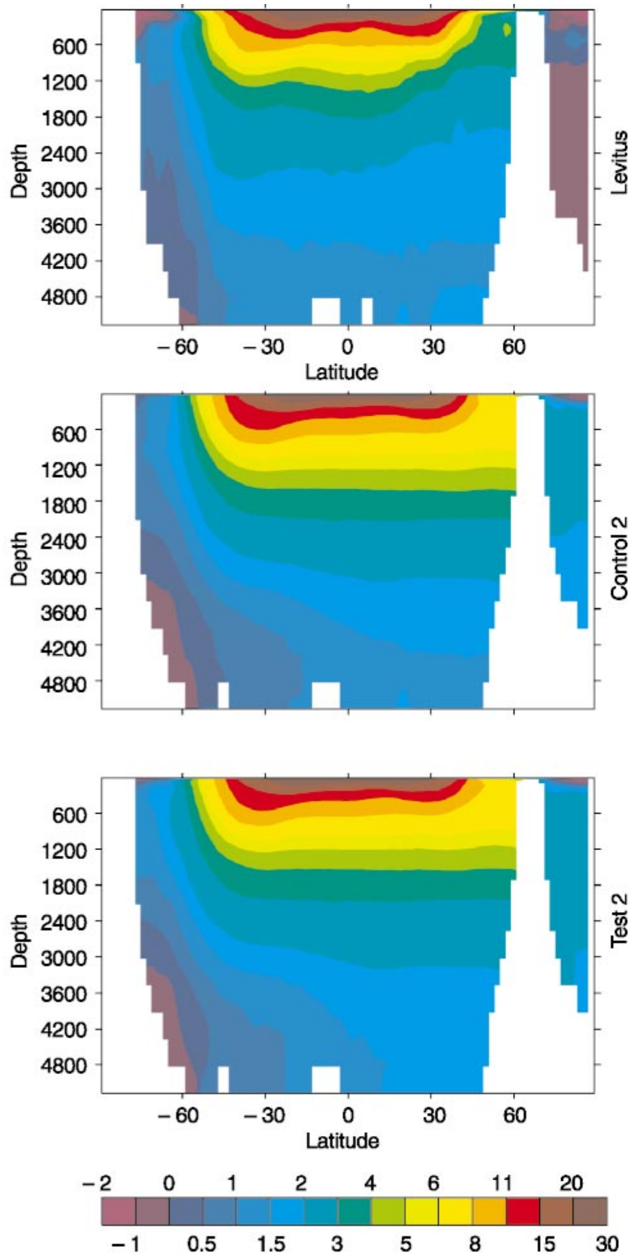

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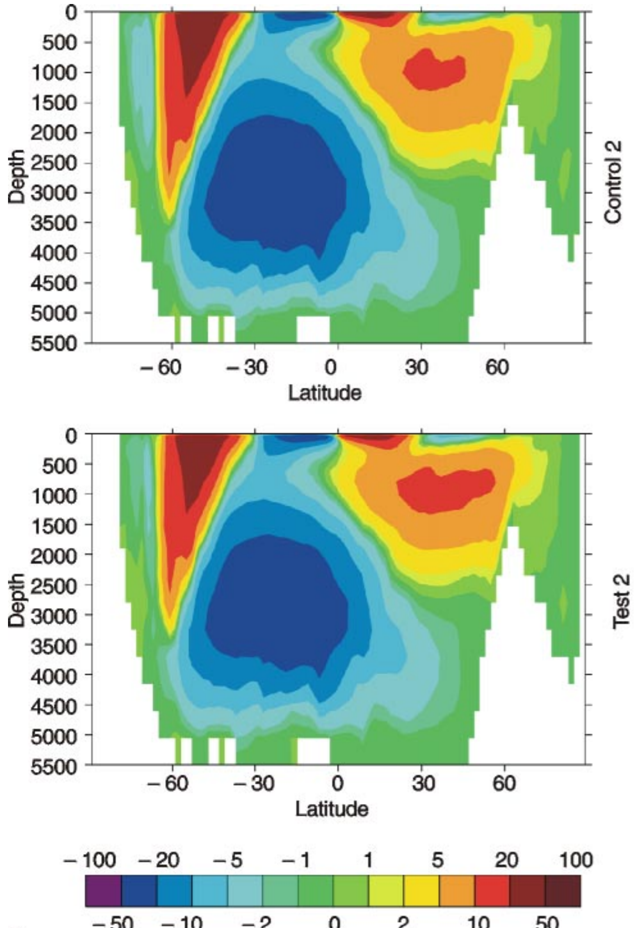
Fig. 5 Latitude-depth sections of potential temperature in the Atlantic Ocean, from observations (Levitus and Boyer, 1994, *top panel*), and as simulated in the control2 and test2 simulations (*middle* and *bottom panels*, respectively). All data shown are annual means, and are averaged in longitude over the Atlantic basin. Temperatures in the test2 simulation are very similar to those on the control2 simulation; both are reasonably realistic

Fig. 6 Same as Fig. 5, except for the Indo-Pacific Ocean. Again, temperatures in the test2 simulation are very similar to those in the control2 simulation, and both are reasonably realistic

5 Conclusions

D&C/C&D showed that results of a 3-dimensional ocean GCM can be dramatically improved by instantaneously mixing salt rejected during formation of sea ice into the subsurface ocean (down to 160 m). This results in much less convective mixing in the Southern Ocean, and much more realistic simulated uptake of transient tracers as well as much more realistic simulated salinities.

We present a new test2 simulation, which extends the work of D&C/C&D by experimenting further with the concept of mixing destabilizing surface fluxes. Whereas



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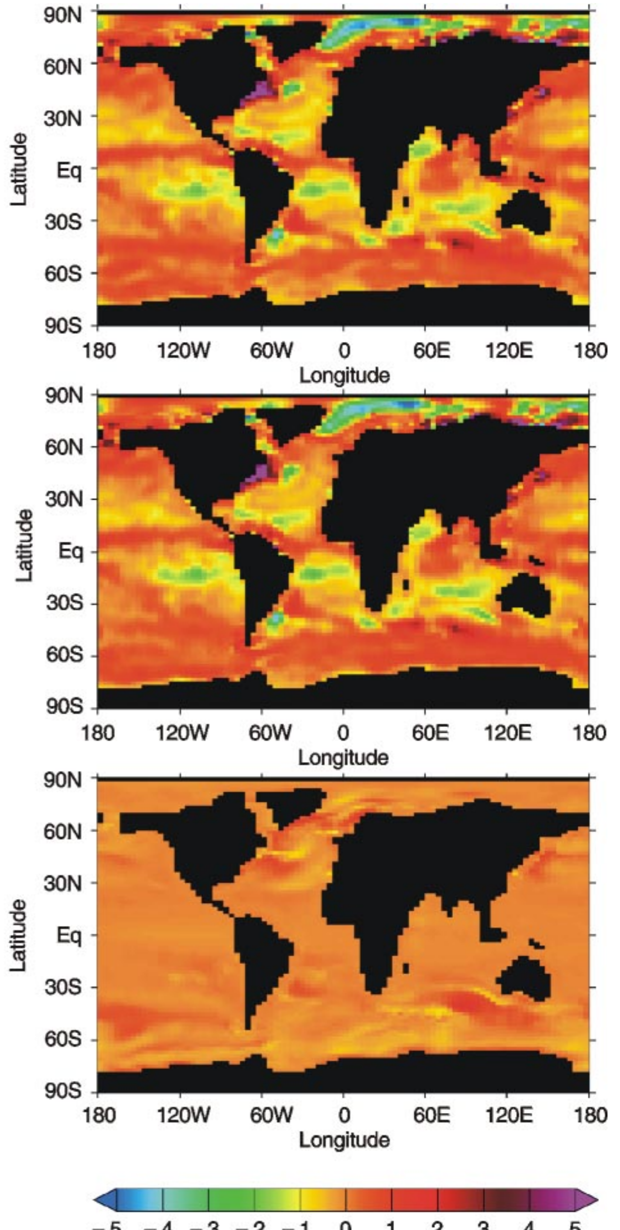

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Fig. 7 Overturning stream functions in the control2 and test2 simulations (*top* and *bottom panels*, respectively) are quite similar. Results shown are annual means

Fig. 8 Surface fluxes of fresh water in the control2 simulation (top panel), test2 simulation (middle panel) and the difference between them (control2-test2; bottom panel). Results shown are annual means, in units of m/y. Positive fluxes represent additions of fresh water to the ocean

D&C/C&D mixed only salt fluxes associated with formation of sea ice, in our test2 simulation, we mix fluxes of both heat and salt when they tend to be destabilizing, in all regions of the ocean. This mimics the fact that heterogeneous surface forcing can cause convection on horizontal spatial scales much smaller than a typical GCM grid cell. We treat this highly subgrid scale convection in the model by vertically mixing not entire grid cells but only the destabilizing surface fluxes. The maximum depth of mixing is calculated based on a specified contrast in potential density with respect to the surface. The results of this test2 simulation show much improved simulated salinities compared to a control2 simulation in which surface restoring of temperature and salinity is performed in the normal way.

These results, and those of D&C/C&D, suggest that ocean model results could be improved by representing the horizontal inhomogeneity of surface buoyancy forcing and of vertical mixing. Parametrizations of convection, such as that of Paluszkiewicz and Romea (1996), which attempt to represent the fact that convection often occurs on horizontal scales which are much smaller than typical GCM grid cells, should in principle go part of the way towards producing improved results similar to those demonstrated here. Our results suggest that this type of parametrization, coupled with the ability to treat the horizontal heterogeneity of surface buoyancy forcing, could produce significant improvements in model results.

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