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9.4 DEEP CONVECTION IN THE ARCTIC: THE EVALUATION OF RESULTS FROM AN OGCM WITH A NEW CONVECTION PARAMETERIZATION

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1. INTRODUCTION

The current generation of ocean general circulation models (OGCMs) uses a convective adjustment scheme to remove static instabilities and to parameterize shallow and deep convection. In simulations used to examine climate-related scenarios, investigators found that in the Arctic regions, the OGCM simulations did not produce a realistic vertical density structure, did not create the correct quantity of deep water, and did not use a time-scale of adjustment that is in agreement with tracer ages or observations (Bacastow 1988; Killworth 1989; Skyllingstad et al. 1990). A possible weakness of the models is that the convective adjustment scheme does not represent the process of deep convection adequately. Consequently, a penetrative plume mixing scheme has been developed to parameterize the process of deep open-ocean convection in OGCMs. This new deep convection parameterization was incorporated into the Semtner and Chervin (1988) OGCM. The modified model (with the new parameterization) was run in a simplified Nordic Seas test basin: under a cyclonic wind stress and cooling, stratification of the basin-scale gyre is eroded and deep mixing occurs in the center of the gyre. In contrast, in the OGCM experiment that uses the standard convective adjustment algorithm, mixing is delayed and is wide-spread over the gyre.

2. CONVECTIVE ADJUSTMENT SCHEMES

Marotzke (1991) found that the parameterization of convection has an impact on the steady state obtained in numerical simulations of the thermohaline circulation. In addition, the choice of convective adjustment scheme has a larger influence on the results from models using mixed boundary conditions as opposed to models using restoring boundary conditions. In the simplest convective adjustment schemes presently used in OGCMs (the "standard" Cox [1984] or Semtner [1974] scheme), the amount of instability that is removed from each profile is determined by the number of adjustment iterations that the user specifies. To invoke the convective adjustment, two vertically adjacent grid points are compared, and if they differ, the temperature and salinity are mixed until they are neutrally stable with respect to each other. Killworth (1989), Smith (1989), and Marotzke (1991) showed that residual instabilities can occur because the finite number of iterations does not completely remove the instabilities. Smith (1989) reported the "standard" convective adjustment scheme is sensitive to both vertical grid structure and model time step. The lack of penetrative vertical mixing under strong convective forcing is a deficiency of this scheme. Bryan and Sarmiento (1985) reported that their simulations failed to transport tritium to the deeper part of the thermocline. Although deeper penetration can be accomplished by increasing the number of convective adjustment interactions, this cannot be done without significant vertical and horizontal mixing in intermediate waters. Another commonly used scheme, the implicit vertical diffusion scheme, tests the stability between adjacent grid points and uses a large vertical diffusivity if the profile is unstable. This technique was adopted to remove the residual instabilities, but it is computationally expensive and less efficient in finding the final boundaries of the convectively adjusted region (Yin and Sarachik 1994). Marotzke (1991) and Yin and Sarachik (1994) developed a "complete" adjustment scheme that uses a locally iterative method to determine the upper and lower boundaries of each convectively adjusted region while keeping the instantaneous adjustment within each unstable region. Yin and Sarachik (1994) found that the "complete" removal of instabilities leads to different model variability in interdecadal simulations. These parameterizations, when used in climate simulations, enforce an implicit assumption that it is not necessary to capture the timing

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or effects of the mechanisms of turbulent mixing in detail. The fact that these parameterizations only remove static stability is unimportant if they adjust the ocean to the correct state. Skyllingstad et al. (1990) showed that the convective adjustment in the Community Modeling Effort (CME) did not mix deep enough to produce realistic water masses (deepest depths 700-900 m). In addition, convection occurred over unrealistically large regions of the Labrador Sea, and the tracer age indicated that it took on the order of one year to bring the tracer to depth. Observations from Clarke and Gascard (1983) showed that convection occurs in isolated patches, penetrates to 1500 m, and occurs in a matter of days. These deficiencies prompted a re-examination of the convective adjustment scheme to build a more physically based parameterization that accomplishes both shallow convective adjustment and deep penetrative convective mixing.

3. THE OCEAN PLUME PARAMETERIZATION SCHEME (OPPS)

The purpose of the ocean plume parameterization scheme (OPPS) was to improve OGCM simulations by including the physics of deep penetrative convection (thermobaric convection) and deep water formation, without adding the complexity of a full, large eddy simulation (LES). To be useful in climate scale OGCMs, the parameterization scheme should have the following attributes: the essential physics must be parameterized in an OGCM grid volume, the code must be compact and fast, the number of adjustable parameters should be minimal, and the model should interface seamlessly with the OGCM from time step to time step. The parameterization scheme accepts temperature and salinity profiles from OGCM grid boxes and simulates the subgrid-scale effects of convection using a buoyancy-forced, vertical mixing scheme that moves water parcels from the surface layer down to their level of neutral buoyancy, simulating the effect of convective plumes. While in transit, the plumes exchange water with the surrounding environment, the bulk of the plume water mass is deposited at the level of neutral buoyancy, and weak upwelling around the plumes maintains an overall mass balance. The process continues until the available buoyant energy of the vertical column is minimized. A full equation of state is used in both the plume model and entrainment rate calculation, thereby accounting for the thermobaric instabilities that may occur. Thermobaric instabilities are caused by the nonlinear thermodynamic characteristics of sea water and are particularly important at high latitudes, where deep water is formed. For code efficiency, a precise look-up table replaces the full equation of state The parameterized plume entrainment rate, which plays a central role in the model physics, is calculated using modified equations based on Turner's (1973) entrainment hypothesis. After the adjustment is complete, the weighted average of the state variables (between plume and environment) is returned to the OGCM. This scheme differs from the convective adjustment techniques currently used in OGCMs, because the parcels penetrate downward with the appropriate degree of mixing with the environment until they reach their level of neutral stability. Another benefit is that the resulting horizontal structure of the density field is not overly homogenized.

The one-dimensional model was tested against observations by initializing the model with hydrographic data and testing the ability to reproduce the time series of hydrography. In addition, the one-dimensional model was tested by comparison with the LES model results of Denbo and Skyllingstad (1994). The LES model was initialized with hydrographic profiles from the Greenland Sea, as was OPPS, and the time evolution was compared. The comparison with this model gave insight into the ability to simulate strong thermobaric events. The depth of penetration, the evolution of the properties, and the time scale of the onset all compared favorably. Finally, the parameterization was tested against existing vertical mixing parameterizations, such as the Kraus-Turner-Killworth (KTK) buoyancy-forced mixed-layer model (Killworth 1985). The OPPS model compared well with the KTK model under general conditions and was able to perform under strongly thermobaric conditions, whereas KTK is unable to correctly simulate thermobaric penetrative convection. The details of the parameterization and the tests of the one-dimensional model are described in Paluszkiewicz and Romea (1994).

4. NORDIC SEAS BASIN EXPERIMENTS

The Parallel Ocean Climate Model (POCM) (Semtner and Chervin, 1988) was configured for the Nordic Seas, and the process of preconditioning was simulated to develop a suitable testbed for evaluating the new deep convection parameterization. The parameterization was incorporated into POCM and the modified model was tested in the Nordic Seas test basin. The new convective parameterization replaced the standard convective adjustment algorithm. The use of the full equation of state, implemented through the look-up table approach, was evaluated against the nonlinear approximation that is generally used. The use of the full equation of state improved the calculation of density at the very low temperatures in the Nordic Seas. The new convective parameterization was tested by evaluating the response to various levels of latent and sensible heat flux and to a range of levels of wind forcing. The results of these experiments are described in the following sections.

4.1 Simulations of Preconditioning

POCM was configured for simulations of preconditioning in the Nordic Seas. The domain extended from 65 °N to 81° N, and 8 °W to 8° E. The horizontal resolution was varied for different cases; simulations were run using 1/8°, 1/4°, 1/2°, and 1° resolution. All the simulations used flat topography with a depth of 2750 m and 16 vertical levels that correspond with those used by Semtner and Chervin (1988). The model was initialized with a climatological profile from the area. We also ran simulations in the Gulf of Lyons for comparison.

Ultimately, different scenarios of cooling and wind stress were evaluated to determine the optimum conditions for generating a preconditioned gyre. By using a combination of heat flux and wind forcing, the vertical stability of the water column was reduced and the characteristic doming of the preconditioned gyre was generated. The wind forcing had the strength and characteristics of the strong, low-pressure systems that have been found in the Greenland Sea, with a maximum of 0.5 dynes (Legutke 1991). The cooling was a constant -200 W m^{-2}. These simulations revealed that the scale of the preconditioned gyre and the preconditioning response time varied, as expected, with the Rossby radius. As a consequence, the simulation of preconditioning is sensitive to the resolution used in the model. The behavior of the gyre-scale circulation and its response to various wind and heat flux conditions is in agreement with the theoretical model of Romea (1976). Cooling and a cyclonic circulation, together, are the essential ingredients for preconditioning. Neither cooling nor a cyclonic circulation alone resulted in the elevation of the pycnocline that is necessary to weaken the vertical stability and facilitate deep convective events. The results from these preliminary simulations were used to select a scenario for testing the new convective adjustment parameterization. An example of the circulation resulting from the preconditioning scenario is shown in Figure 1.

4.2 Simulations with the OPPS and the Standard Convection Scheme

POCM, with OPPS incorporated, was run in the Nordic Seas test basin and compared with a "twin" POCM experiment that uses the standard convective adjustment algorithm. The test runs used 1/4° and 1/2° resolution in the horizontal and were run for 100 days. The tests used the same model configuration, vertical resolution, domain, and flat bottom. The temperature and salinity were initialized from a profile from Rudels et al. (1989). A cyclonic wind stress with a maximum of 0.5 dynes, a sensible heat flux of -100 W m^{-2}, and a latent heat flux of 30 W m^{-2}, were used to generate a preconditioned gyre and stimulate convection.

The test basin was subjected to wind forcing for 50 days to generate a cyclonic circulation (Figure 1).

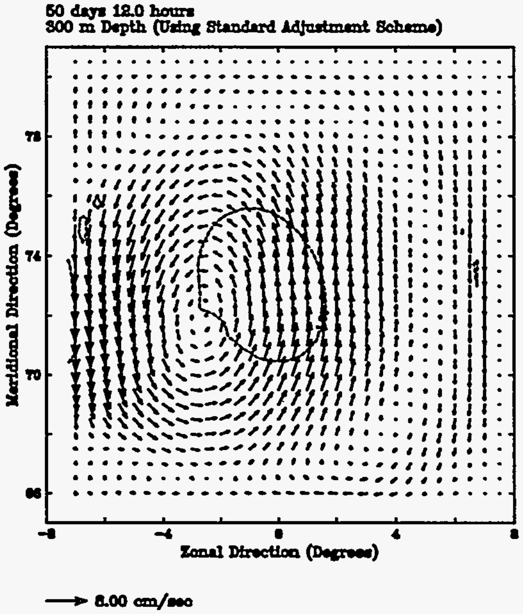


Figure 1. Horizontal section of velocity and temperature at 300 m after 50 days of a cyclonic wind stress. A potential temperature contour, -1.34°C, shows the beginning of the doming of the temperature and density fields.

Following the 50 days of wind stress, the cooling and latent heat flux were initiated. During the next 50 days the doming of the isopycnals and isotherms evolved. In the simulation using OPPS (the new convective parametrization) the convective activity is concentrated in the center of the doming. In contrast, in the simulation using the standard convective algorithm, the convective activity is found along the edges of the gyre (high shear regions) and along the thermocline. Convective activity was measured by using a counter that is triggered when the code performs a convective adjustment. At day 82.5, a snapshot from each simulation shows that doming is occurring in the center of gyre and that in the case using OPPS, there is significant mixing through the water column. In the case with the standard convective adjustment, doming is not well defined and the mixing is taking place along the thermocline. At day 85, the doming breaks the surface and the thermocline begins erode, whereas in the standard convective adjustment case, mixing is still confined to the thermocline region (Figure 2). A possible explanation for the evolution of these fields (temperature, salinity, and density) is that a spurious vertical velocity from the high shear regions near the boundary triggers a disturbance along the thermocline that in turn requires convective adjustment. This pattern of thermocline disturbance continues so that all of the effective mixing occurs in this region. The simulation with OPPS differs because it accommodates partial mixing through the vertical levels, governed by the available buoyant energy budget, using entrainment physics to govern the degree of mixing. Consequently, the stability is quickly found by creating a mixed, stable water parcel.

In the standard convective adjustment case, two vertically adjacent particles are mixed to remove the instability. The top five to six levels have very small changes in the temperature and salinity variables; therefore, the mixing between the adjacent levels removes small amounts of the instability, and the evolution of the cooled feature proceeds very slowly.

These results indicate that the OPPS convection scheme leads to more penetration and that there is less horizontal homogenization of the intermediate levels than with the standard adjustment scheme (Figure 2).

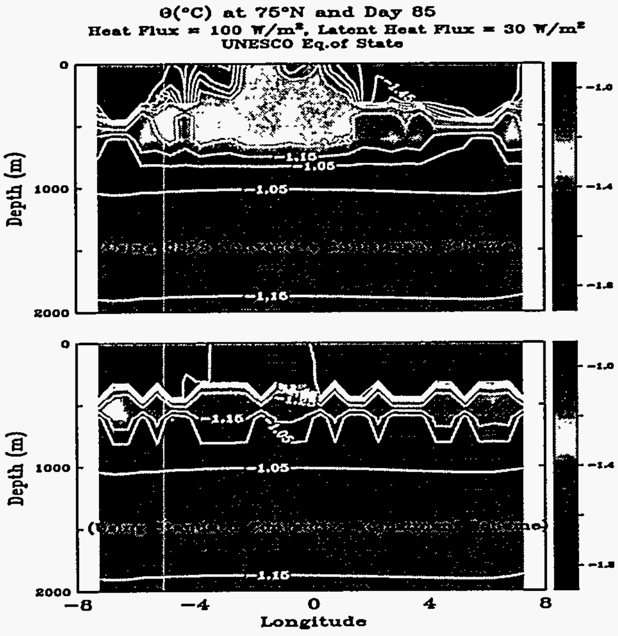


Figure 2. The potential temperature versus depth from a section at 75°N in an idealized Nordic Seas domain. POCM was spun-up for 50 days using a cyclonic wind stress, then cooling was initiated. The top panel shows the convective cells forming in a simulation from POCM using OPPS for a convective adjustment scheme. The lower panel is from POCM using the standard convective adjustment scheme; notice that in the bottom panel, the convective adjustment occurs throughout the domain rather than in the domed, preconditioned gyre and is not penetrative.

In the horizontal plane, an X-Y slice at 300 m shows that the mixed area in the center of the dome has irregular edges for the simulation using OPPS. This reflects the influence of the partial mixing, as opposed to the overall homogenization that the standard convection algorithm generates (Figure 3a and b).

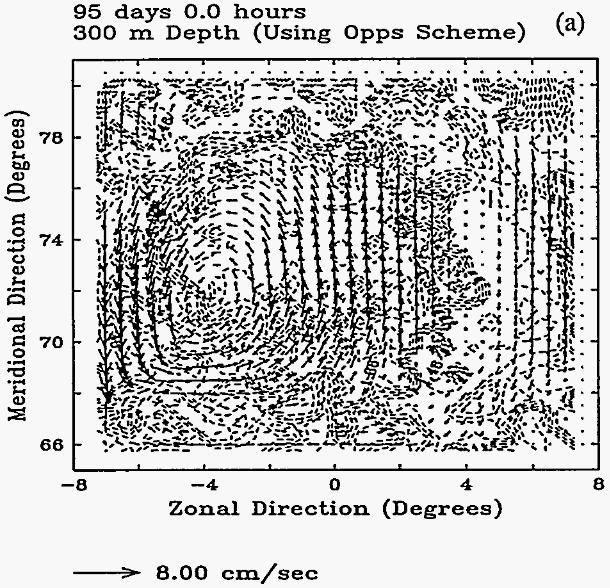
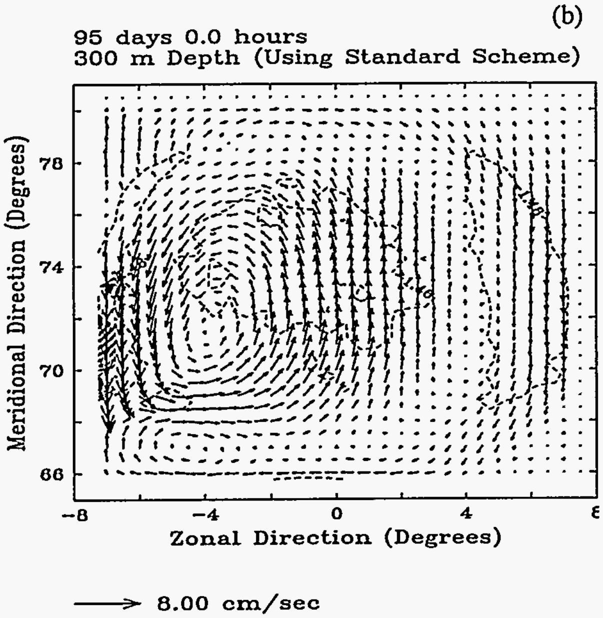


Figure 3. Horizontal section of velocity and temperature at 300 m after 95 days of a cyclonic wind stress and cooling starting on day 50. Potential temperature contours show the extent of the mixing within the gyre.

(a) Using OPPS scheme.



(b) Using standard scheme.

5. CONCLUSIONS AND FUTURE PLANS

The natural extension of this work will be to compare simulations using OPPS with simulations from using the implicit vertical diffusion scheme and the "complete" adjustment scheme. A more complete removal of the instabilities by OPPS is governed by the available buoyant energy (ABE) in the OGCM grid column, in contrast to removal by a user-specified number of convective passes. To test the completeness of the removal of instabilities, simulations similar to that of Yin and Sarachik (1994) will be performed. We would like to test OPPS in the global models over long time scales, and at coarse resolution, in order to determine the sensitivity of the thermohaline circulation to this change in parameterization. In addition, we will investigate the role of the surface boundary conditions in triggering deep convection events. In climate-scale simulations, a restoring surface boundary condition is used on the temperature and salinity fields. It is common to use a month time scale on the restoring time; the climatological monthly means are generally used as the forcing data sets. We plan to evaluate how this method triggers deep convective events in comparison to how a heat flux and salinity flux boundary condition triggers events. Killworth (1983) and Chu and Gascard (1991) noted that deep convection is believed to be triggered by a combination of preconditioning of the gyre-scale circulation along with intense cooling events. A better temporal resolution (than monthly mean) of these triggering mechanisms may be necessary to achieve the full value of the convective parameterization. The use of a heat and salt flux condition, as opposed to a monthly restoring boundary condition, could facilitate this temporal resolution and could facilitate coupling with the atmospheric models.

6. ACKNOWLEDGMENTS

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