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Isopycnal mixing and the Veronis effect in an ocean general circulation model

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ABSTRACT

In this study we have run a number of numerical simulations to examine the 'Veronis effect' in an ocean general circulation model. This effect is characterized by anomalous interior downwelling, east of the western boundary current of an ocean basin. The impact of varying the horizontal diffusivity and the use of an isopycnal mixing parameterization are examined.

Several diagnostics are used. The net volume transport for a sector in the southern part of the domain, east of the western boundary is found to be the clearest indicator of the strength of the Veronis effect.

This effect is found to depend crucially on the horizontal diffusivity. The use of an isopycnal mixing parameterization significantly mitigates the interior downwelling problem but is constrained by the required use of a background horizontal diffusivity. Thus, in a geopotential coordinate model an isopycnal mixing parameterization enables the use of a significantly reduced horizontal diffusivity while emphasizing the mixing along isopycnals.

1. Introduction

The "Veronis effect" was first noted by Veronis (1975) in a review of a numerical simulation of the North Atlantic (Holland, 1971). In this simulation there was substantial interior downwelling flow perpendicular to geopotentials, contrary to expectation (Stommel, 1958). Veronis speculated that the anomalous downwelling was the result of the use of a vertical/horizontal mixing sub-grid scale parameterization of temperature and salinity. This parameterization is used to account for the effect of unresolved ocean eddies. Veronis suggested that the use of an isopycnal/diapycnal mixing parameterization would mitigate this downwelling. Throughout much of the domain isopycnals (surfaces of constant potential density) are essentially coincident with geopotentials. In the northern convection region and along the western boundary, isopycnals outcrop and horizontal mixing causes a diapycnal (cross isopycnal) flux of heat and salt. There would thus be a spurious heat flux in those regions of steep isopycnal sloping. To balance this flux, enhanced upwelling of

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cold water from the deep ocean is required. To satisfy mass continuity constraints, downwelling is required elsewhere. Veronis argued that the interior downwelling in Holland's simulations was the result of this process.

McDougall and Church (1985) invoked a similar reasoning to explain large density fluxes in the same region in the results of Cox and Bryan (1984). Both Cox and Bryan and Holland employed large horizontal eddy diffusivities ($A_H = 1.0 \times 10^8$ cm^2/s) in their mixing parameterization. Veronis found that the interior downwelling decreased with the use of a lower horizontal diffusivity. McDougall and Church (1985) recommended the use of an isopycnal mixing parameterization to reduce the spurious density flux. Redi (1982) derived the appropriate transformation tensor for isopycnal mixing in a model using a geopotential coordinate system. Cox (1987) produced the necessary computer code to implement this scheme. Several investigators have used this parameterization with the GFDL (Bryan, 1969; Cox, 1984) ocean general circulation model (Lin and Gough, 1990; Cummins *et al.,* 1990; Gerdes *et al.,* 1991; Gough, 1991; Manabe *et al.,* 1991; Gough and Lin, 1992; England, 1993; Hirst and Cai, 1994; Gough and Welch, 1994). In a comparison study Gough (1991) found that the isopycnal version of the model produced a slightly weaker meridional overturning streamfunction, a shallower thermocline and colder bottom water temperature than a similarly constructed model using horizontal mixing.

Cummins *et al.* (1990) examined the parameterization of vertical diffusion in the GFDL model. The isopycnal mixing parameterization was used on one of their experiments. A diapycnal diffusivity ratio was used as a measure of the cross isopycnal flow near the western boundary. This ratio was calculated by comparing the vertical diffusivity resulting from cross isopycnal flow with the nominal value for the vertical diffusivity. They found that there was indeed less cross isopycnal flow in the isopycnal case, but this reduction was limited by a background horizontal eddy diffusivity required for numerical stability.

Gough and Welch (1994) also examined the Veronis effect by using a less direct diagnostic: the total number of downwelling points. They found a strong dependence on the horizontal background diffusivity and the maximum allowable isopycnal slope; the latter is yet another numerical constraint. Some evidence suggested that this diagnostic may not be the clearest indicator of the Veronis effect.

In this paper we examine two models which used respectively the vertical/horizontal mixing and the diapycnal/isopycnal mixing parameterizations. The horizontal diffusivity is varied in the first model and in the second model, both the isopycnal diffusivity and background horizontal diffusivities are varied. Several new diagnostics are used in addition to the total number of downwelling points to examine the Veronis effect. In Section 2 the model is described together with a description of the experiments. The results and discussion are presented in Section 3, and the conclusions in Section 4.

Table 1. The background horizontal diffusivities, isopycnal diffusivities and maximum allowable isopycnal slope for studies using an isopycnal mixing parameterization.

Study	A_B (10^7 cm^2/s)	A_I (10^7 cm^2/s)	δ_m
Lin and Gough (1990)	0.2	0.8	0.01
Cummins *et al.* (1990)	0.2	1.0	0.01
Gough (1991)	0.2	0.8	0.001–0.1
Manabe *et al.* (1991)	0.5	2.5	0.01
Gough and Lin (1992)	0.2	0.8	0.01
England (1993)	0.375–0.75	1.0–5.0	0.01
Hirst and Cai (1994)	0.7	1.0–5.0	0.01
Gough and Welch (1994)	0.1–2.0	0.5–5.0	0.001–0.1
Present study	0.2–0.5	1.0–3.75	0.01

2. Model description and experimental design

a. Model. The model used in this work is the widely distributed Bryan-Cox ocean general circulation model. It is based on the pioneering work of Bryan (1969). A detailed description of the model can be found in Cox (1984). The notation used is standard.

The model domain approximates the North Atlantic extending from 20–70N and 60° of longitude. There are ten vertical levels of increasing depths, ranging from 50 m near the surface to 1000 m at the bottom, giving a total depth of 4000 m. The horizontal resolution is $2° \times 2°$ resolution in longitude and latitude. The side walls are vertical and the bottom is flat. Further details about the model configuration and boundary conditions can be found elsewhere (Gough, 1991; Gough and Lin, 1992; Gough and Welch, 1994).

As discussed in the Introduction, an alternative parameterization of the sub-grid scale eddy processes is diapycnal/isopycnal mixing, rather than the traditional vertical/horizontal (geopotential) mixing (Redi, 1982; Cox, 1987).

There are two numerical constraints in using the isopycnal mixing parameterization. A background horizontal diffusivity is required, and there is a limit on the maximum allowable isopycnal slope. The former is required to subdue grid point noise, and the latter is a diffusive constraint (Cox, 1987). Their effect is to render the parameterization less "isopycnal," resulting in enhanced diapycnal fluxes especially in regions of strong isopycnal sloping.

Listed in Table 1 are values of the background horizontal diffusivities, isopycnal diffusivities, and maximum allowable isopycnal slopes for previous work with the isopycnal parameterization. A value of the background horizontal diffusivity, A_B, below 0.2×10^7 cm^2/s has not produced a stable equilibrium when the standard maximum allowable isopycnal slope of 0.01 has been used (Gough, 1991; Gough and Welch, 1994). In this work we use values of the background horizontal diffusivity corresponding to the lower range of stable values from Table 1 ($A_B = 0.2 - 0.5 \times 10^7$ cm^2/s). The work of Gerdes *et al.* (1991) is not included in Table 1.

Table 2. The values of the different diffusivities used in the experiments.

Case	A_H (10^7 cm²/s)	A_I (10^7 cm²/s)	A_B (10^7 cm²/s)
1	0.2	—	—
2	0.5	—	—
3	1.0	—	—
4	2.5	—	—
5	4.5	—	—
6	—	1.0	0.2
7	—	1.0	0.3
8	—	1.0	0.4
9	—	1.0	0.5
10	—	2.25	0.3
11	—	3.0	0.4
12	—	3.75	0.5

They circumvented the two numerical constraints by using vertical/horizontal mixing for all boundary points and by using a locally reduced isopycnal diffusivity in regions of steep slopes.

Gough and Welch (1994) explored the sensitivity of the model results to the maximum allowable isopycnal slope and the background horizontal diffusivity, including the Veronis effect. The parameter space with respect to seven input parameters was explored. In the Appendix we re-examine the results of the 51 experiments to give us a guideline in the selection of appropriate values for the horizontal background diffusivity in order to insure stable flows. All simulations in this study are stable.

b. Experiments. Twelve numerical experiments with different diffusivities are performed (Table 2). In experiments 1–5, the observation that the Veronis effect is weaker for lower values of horizontal diffusivity (Veronis, 1975) is examined using a model that employs vertical/horizontal mixing. The following seven experiments use the isopycnal mixing parameterization. In experiments 6–9, the background horizontal diffusivity is incremented to examine its impact on the various diagnostics of the Veronis effect. Experiments 10–12 use the same values of the background horizontal diffusivities, but with larger values of the isopycnal diffusivity. The magnitude of the background diffusivities are chosen to insure numerical stability. The horizontal mixing cases use a vertical diffusivity of $A_V = 1.0$ cm²/s to correspond to the value chosen for the diapycnal diffusivity (A_D).

3. Results and discussion

The results are divided into two sections. First, the nature of the Veronis effect is examined. Several diagnostics are used to illustrate the impact of variations in the

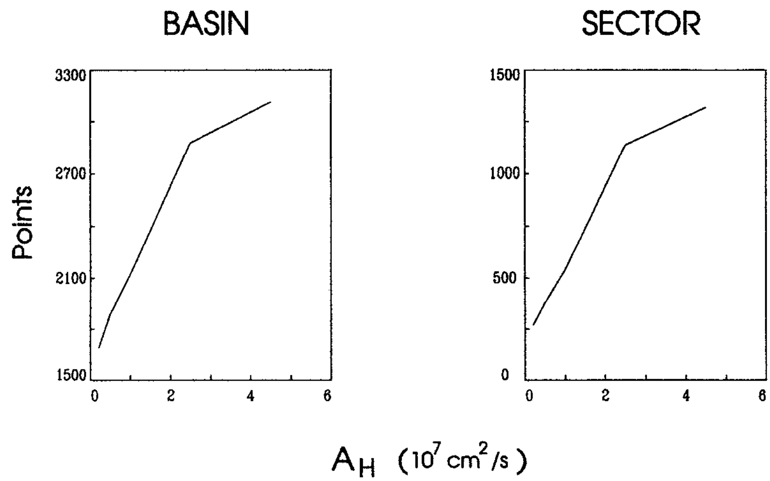

Figure 1. The number of downwelling points versus the horizontal diffusivity, A_H, for (a) basin, and (b) sector.

horizontal diffusivity. In the second section the mitigating influence of the isopycnal mixing parameterization is explored.

a. The Veronis effect. In Gough and Welch (1994) the total number of downwelling points in the ocean basin was used as a measure of the Veronis effect. In this model configuration there are 5,796 model points where downwelling can occur. This diagnostic is used for the first five experiments listed in Table 2. In these experiments the model uses horizontal mixing and the horizontal diffusivity is increased with each successive experiment. Figure 1a depicts the total number of downwelling points as a function of the horizontal diffusivity. The number of downwelling points increases with horizontal diffusivity which is consistent with the Veronis effect. Veronis (1975) noted that the new downwelling points would occur east of the western boundary in the southern part of the domain. To test this a second downwelling diagnostic is used. A sector of the model domain is examined, 23–45N, 57–13W and for levels 5 to 10. The lower levels are chosen in order to separate the Veronis downwelling from that generated by the wind driven Ekman circulation. This sector comprises 25% of the grid points in the domain. The sector results are shown in Figure 1b. By comparing this to Figure 1a we can see that the variation in downwelling points in this sector accounts for most of the variation for the entire basin. This result is again consistent with the Veronis effect.

The number of downwelling points does not necessarily indicate the strength of the downwelling. We thus use a new diagnostic, the volume transport (VT), which is defined as the sum of the downwelling velocities (w_i) weighted by the volume element (dV_i),

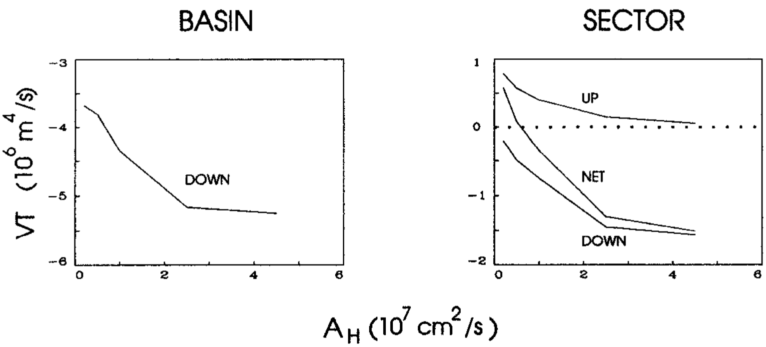

Figure 2. The volume transport, *VT*, versus the horizontal diffusivity for (a) basin, and (b) sector. The volume transport is measured in 10^6 m^4/s.

$$VT = \Sigma_i w_i dV_i \tag{1}$$

where the index i refers to all grid points in the basin or sector. Physically, this diagnostic corresponds to the volume integral of the vertical momentum per unit mass. In Figure 2a this diagnostic is shown for the basin. The strength of the downwelling over the entire domain does increase with increasing horizontal diffusivity. Over the basin, the strength of the upwelling must also increase correspondingly. The vertical circulation is thus intensified, but this does not necessarily validate the Veronis hypothesis. To do this, we examine the sector diagnostic (Fig. 2b) which includes both the upwelling and net volume transports. In the sector, the upwelling volume transport need not balance exactly the downwelling volume transport. In fact, the upwelling decreases as the magnitude of the downwelling increases. For low horizontal diffusivity the net transport is positive, consistent with the Stommel view of slow upwelling in the southern part of the domain. However, as the horizontal diffusivity increases, the downwelling strengthens and the upwelling weakens, giving a negative net transport. This is an indication of the prevalent interior downwelling as noted by Veronis in the Holland (1971) results.

b. Isopycnal mixing and the Veronis effect. Veronis and others have speculated that the use of an isopycnal mixing parameterization rather than the traditional horizontal mixing would mitigate, if not eliminate, the interior downwelling problem. Experiments 6–12 of Table 2 are designed to test this hypothesis. Two factors are of particular interest: the impact of increasing isopycnal diffusivity, and the effect of the required background horizontal diffusivity.

For this analysis we look at the net volume transport in the sector which was found in the previous section to be the clearest indicator of the Veronis effect. In Figure 3 the net volume transport is plotted for the horizontal and isopycnal cases. The horizontal case is plotted as a function of horizontal diffusivity and the isopycnal cases as a function of the isopycnal diffusivity. Throughout the range of values the

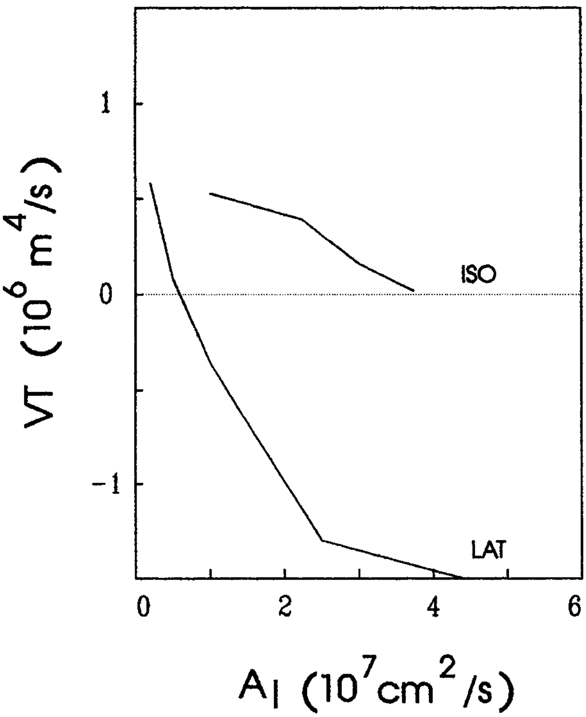

Figure 3. The net volume transport versus isopycnal diffusivity for the isopycnal cases for the sector. Included in the plot is the corresponding horizontal mixing case.

isopycnal case has a positive net volume transport indicating overall upwelling in the sector. The horizontal case is positive only for the lowest values of the horizontal diffusivity and becomes increasingly negative for larger values. The net volume transport of the isopycnal case does decrease with increasing isopycnal diffusivity. As noted in Section 2a, larger values of the isopycnal diffusivity require larger values of the horizontal background diffusivity. In Figure 4 the net volume transport is presented for the two cases. This time the isopycnal case is plotted as a function of the horizontal background diffusivity. Note that the range of diffusivity values is much smaller than in Figure 3. As the largest background horizontal diffusivity used was $A_B = 0.5 \times 10^7$ cm^2/s, only those horizontal cases with horizontal diffusivity less than this value are plotted. The isopycnal and horizontal cases give much the same results. Since the background horizontal diffusivity mixes along geopotentials rather than isopycnals, there is some cross isopycnal flow in the western boundary leading to the appearance of the Veronis effect.

The use of the isopycnal mixing parameterization clearly reduces the amount of downwelling in the southern part of the model domain thereby mitigating the Veronis effect. This mitigation is however constrained by the required use of the horizontal background diffusivity.

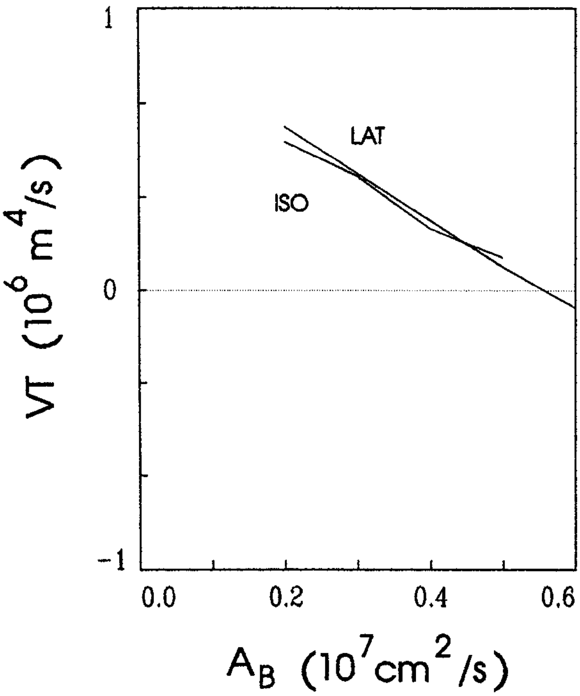

Figure 4. The net volume transport versus the background horizontal diffusivity for the isopycnal case for the sector. Included in the plot is the corresponding horizontal mixing case.

4. Conclusions

In this study we examine the nature of the Veronis effect. The experiments are designed to assess the effect of increasing horizontal diffusivity, and the use of an isopycnal mixing parameterization.

Several diagnostics are used to measure the presence and strength of the Veronis effect. The number of downwelling points in the entire basin and in a smaller sector in the southern half of the domain are used initially. The sector diagnostic proves to be a clearer indicator of the presence of the Veronis effect. Most of the increase in downwelling points occurs in this sector. To measure the strength of the Veronis effect, a volume transport is calculated. The net volume transport in the sector is found to be a better measure of the strength of the Veronis effect. Using the net transport, we separate the Veronis effect from the overall intensification or diminution of the vertical flow as a result of horizontal diffusivity variations.

The horizontal cases show that the Veronis effect increases with increasing horizontal diffusivity, a result common to all diagnostics. The net volume transport for the sector is positive only for low horizontal diffusivities, and it becomes increasingly negative for larger diffusivities. This is consistent with the Veronis hypothesis. With increased horizontal diffusivity, there is more cross isopycnal heat flux near the western boundary, resulting in increased interior downwelling.

The isopycnal results show that the use of the isopycnal mixing parameterization mitigates the interior downwelling found in the corresponding horizontal mixing model. There is a positive net volume transport for the entire range of isopycnal diffusivities, in contrast to the horizontal results. Consistent with the horizontal cases the Veronis effect is found to increase with the required background horizontal diffusivity. Models that include the isopycnal mixing parameterization thus benefit by a reduction of spurious interior downwelling.

The model used in this study is non-eddy-resolving with a resolution typical of that used in climate models. This necessitates the use of large diffusivities for vertical and lateral mixing. Models of finer resolution (e.g., eddy-resolving) do not require as large a horizontal diffusivity and therefore are likely to have a weaker Veronis effect and hence reduced interior downwelling.

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APPENDIX

We re-examine the 51 experiments reported in Gough and Welch (1994). These were simulations using a wide range of values for the eddy viscosities, eddy diffusivities, maximum isopycnal slope and peak wind stress for the isopycnal version of the Bryan-Cox ocean general circulation model. Fifteen of the experiments exhibited unstable behavior. Unstable flows consist of explosive and non-convergent oscillatory behavior and the appearance of "negative" diffusion leading to a violation of the second law of thermodynamics. The explosive cases can be easily avoided by insuring the diffusive constraint derived by Cox (1987) is satisfied,

$$\delta_m < \left(\frac{\Delta a \Delta z}{4A_I \Delta t}\right)^{1/2} \tag{A1}$$

where Δa, Δz, and Δt refer to the horizontal grid spacing, vertical grid spacing and timestep respectively.

Non-convergent oscillatory behavior occurred when the values of the isopycnal and background diffusivity were low. Negative diffusion appears to occur under two circumstances. First, it occurs when the background diffusivity is at the low end of its range (0.1×10^7 cm^2/s). The second instance depends on the relative values of the isopycnal diffusivity, horizontal background diffusivity, maximum allowable slope and the diapycnal diffusivity.

For the 51 experiments the following relation indicates a threshold for the

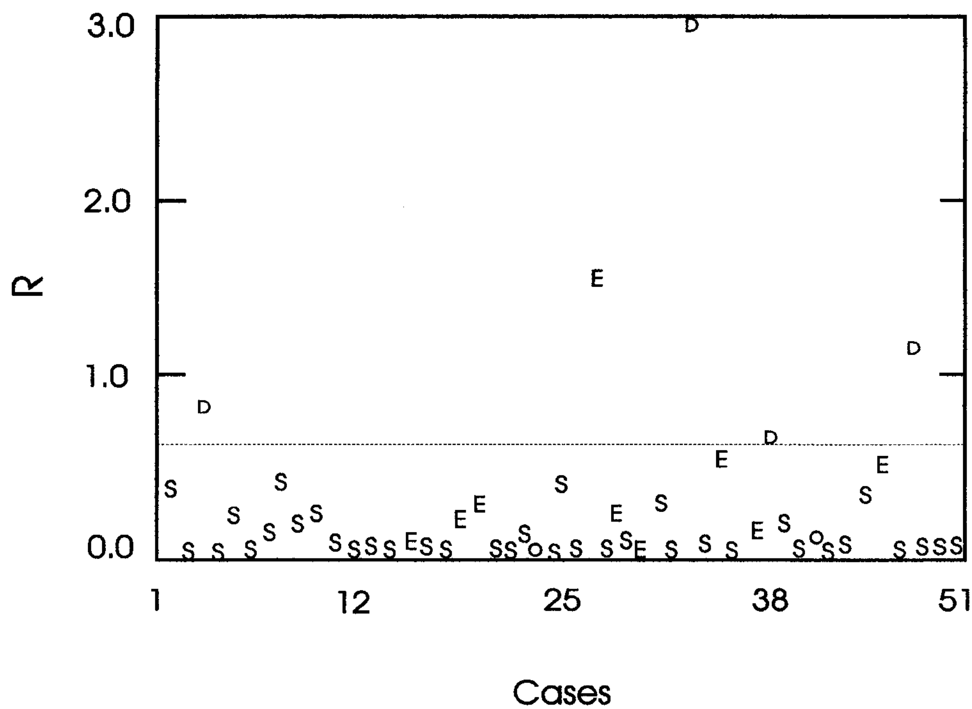

Figure 5. Scatter diagram of a stability threshold ratio for each of the 51 cases in Gough and Welch (1994). Explosive cases are denoted by an "E," oscillatory cases by an "O," cases which have negative diffusion by a "D" and stable cases are indicated by an "S."

appearance of negative diffusion,

$$\frac{A_I}{A_B}\frac{\delta_m^{1/2}}{A_D} < 0.6 \text{ cm}^{-2}\text{ s} \tag{A2}$$

Figure 5 is scatter plot of the 51 experiments and this ratio. All diffusive cases, indicated by "*D*," are above the $R = 0.6$ line. Accompanying these cases are explosive cases indicated by "*E*." Stable and oscillatory cases are denoted by "S" and "O" respectively. For the purposes of this work a simpler ratio may be employed. The maximum allowable isopycnal slope and the diapycnal diffusivity are fixed at $\delta_m = 0.01$ and $A_D = 1.0$ cm^2 /s. This reduces the stability requirement to the constraint that the isopycnal diffusivity cannot exceed the horizontal background diffusivity by a factor of 6.0. In this study a more conservative value of 5.0 was used.

REFERENCES

Bryan, K. 1969. A numerical method for the study of the circulation of the world ocean. J. Comput. Phys., *4,* 347–376.

Cox, M. 1984. A primitive equation, three dimensional model of the ocean. GFDL Ocean Tech. Report No. 1, Princeton, NJ.

—— 1987. Isopycnal diffusion in a z-coordinate ocean model. Ocean Modelling, *74,* 1–5.

Cox, M. and K. Bryan. 1984. A numerical model of the ventilated thermocline. J. Phys. Oceanogr., *14,* 674–687.

Cummins, P., G. Holloway and A. Gargett. 1990. Sensitivity of the GFDL ocean general circulation model to a parameterization of vertical diffusivity. J. Phys. Oceanogr., *20,* 817–830.

England, M. 1993. Representing the global-scale water masses in ocean general circulation models. J. Phys. Oceanogr., *23,* 1523–1552.

Gerdes, R., C. Koberle and J. Willebrand. 1991. The influence of numerical advection on the results of ocean general circulation models. Clim. Dyn., *5,* 211–226.

Gough, W. 1991. Lateral and isopycnal mixing of passive and active tracers in an ocean general circulation model. Ph.D. thesis. McGill University. Montreal, Canada, 147 pp.

Gough, W. and C. Lin. 1992. The response of an ocean general circulation model to long time-scale surface temperature anomalies. Atmosphere-Ocean, *30,* 653–674.

Gough, W. and W. Welch. 1994. Parameter space exploration of an ocean general circulation model using an isopycnal mixing parameterization. J. Mar. Res., *52,* 773–796.

Hirst, A. and W. Cai. 1994. Sensitivity of a world ocean GCM to changes in subsurface mixing parameterization. J. Phys. Oceanogr., *24,* 1256–1279.

Holland, W. 1971. Ocean tracer distributions—a preliminary numerical experiment. Tellus, *23,* 371–392.

Lin, C. and W. Gough. 1990. Tracer distribution in ocean models with lateral and isopycnal diffusion. J. Mar. Systs., *1,* 209–216.

Manabe, S., M. Spelman and K. Bryan. 1991. Transient responses of a couple ocean-atmosphere model to gradual changes of the atmospheric CO_2. Part 1. Annual mean response. J. Clim., *4,* 785–818.

McDougall, T. and J. Church. 1985. Pitfalls with the numerical representation of isopycnal and diapycnal mixing. J. Phys. Oceanogr., *17,* 1950–1964.

Redi, M. 1982. Oceanic isopycnal mixing by coordinate rotation. J. Phys. Oceanogr., *12,* 1154–1158.

Stommel, H. 1958. The abyssal circulation. Deep-Sea Res., *5,* 80–82.

Veronis, G. 1975. The role of models in tracer studies, *in* Numerical models of Ocean circulation, National Academy of Science, 133–146.

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