Comments on "On the Importance of Vertical Resolution in Certain Oceanic General Circulation Models"

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18 July 1990 and 15 April 1991

In a recent paper, Weaver and Sarachik (1990) made a misleading quotation of Suginohara and Fukasawa (1988, hereafter referred to as SF) and Suginohara and Aoki (1991, hereafter referred to as SA, whose title was changed after submission to *J. Mar. Res.*) to demonstrate that all secondary circulation cells at the equator obtained so far in numerical models are due to insufficient vertical resolution. In their introduction, they first quoted, "In many recent modeling studies there have been very curious features observed in the solutions at the equator. Most noteworthy of these is a cell that shows up in the meridional overturning streamfunction, centered at a depth of around 3000 m (SA and other papers). This cell is driven by intense downwelling at the eastern boundary, is of comparable magnitude to the primary cell driven by deep water formation at high latitudes, and flows in opposite sense to this primary cell." A cell obtained in SA is completely different from the one described above. The cell in SA flows in the same sense as the primary cell and there is no intense vertical motion at the eastern boundary in the equatorial region. They next quoted, "There have also been other curious features that have shown up in equatorial regions of model simulations. For example, SF found that their eastern equatorial meridional flow changed sign at each of their five levels. When they increased their resolution to nine levels, they found that the flow changed sign eight times." It is difficult to understand what they meant to indicate by the eastern equatorial meridional flow. But, as best as we can judge, they seem to be referring to the cross-equatorial flow in the eastern region. It is inadequate to refer to this flow, because they are just looking at computational noise with negligibly small magnitude. This is evident in the meridional circulation along meridional sections and in the horizontal velocity fields. What SF really tried to say is the following: The zonal flow along the equator changed sign at each of the five levels (the stacked jets along the equator), although the associated meridional flows just outside the equator were organized. When the resolution was increased to nine levels to confirm that this phenomenon is not computational, it was found that the vertical scale of the stacked jets was comparable to that for the five-level model. Then it was concluded that the stacked jets and associated meridional flows are a dynamical consequence. It is necessary to mention here that the

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TABLE 1. Vertical grid size in meters.

Model layer	SA (12 levels)	Present experiments (19 levels)
1	50	50
2	70	70
3	110	110
4	170	170
5	250	200
6	350	200
7	500	200
8	500	250
9	500	250
10	500	250
11	500	250
12	500	250
13		250
14		250
15		250
16		250
17		250
18		250
19		250

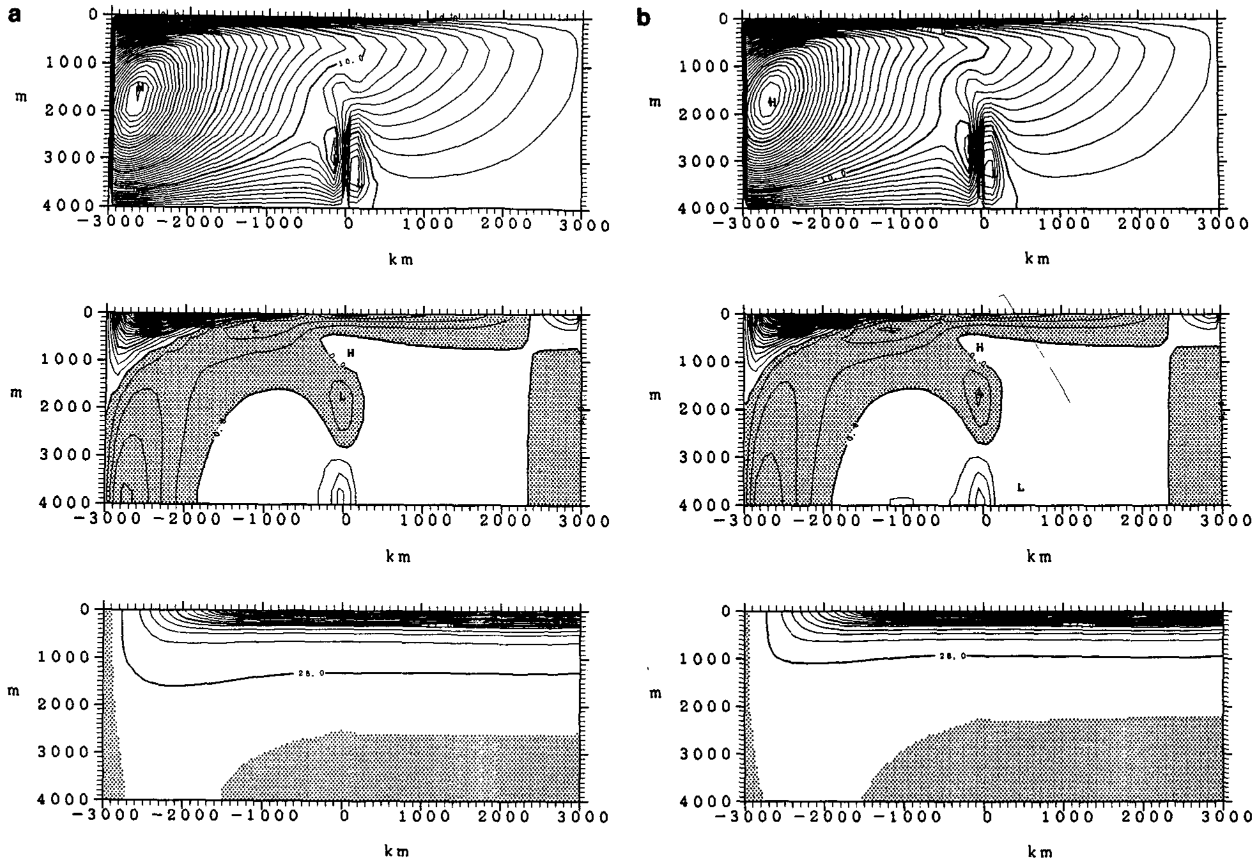

FIG. 1. Streamfunction of zonal-mean circulation (upper) and zonal averages of zonal flow (middle) and density (lower) for SA (a) and the finer vertical resolution case (b). For the stream function, the contour interval is 10^{10} cm^3 s^{-1}. For the zonal flow, the contour interval is 0.5 cm s^{-1} and the shaded areas indicate the westward flow. For the density, the contour interval is 0.2 in σ_t units. The shaded areas indicate σ_t greater than 28.03 for (a) and 28.06 for (b).

models used in SF and SA are carefully designed not to produce the artificial cells that they showed in Fig. 2 of their paper, i.e., instead of the centered difference, a weighted upcurrent scheme is taken for the vertical advection term of density, where the weight that is constant in the whole domain is determined empirically not to induce false increase and/or decrease in density at every grid point. Furthermore, the horizontal grid size is taken to be 100 km in order to resolve the radius of deformation for higher vertical modes, as the stacked jets consist of many vertical higher modes (see SA).

From the preceding discussion and the detailed structure of the stacked jets and associated meridional circulation obtained in SA, it shall easily be understood that this feature is not computational. Here, however, to further confirm this, we show results of two cases that are direct extensions of SA. One is a case where the vertical resolution of SA is doubled for the deep water, as shown in Table 1, and the other is a case where the horizontal resolution is reduced by half; i.e., the horizontal grid size is 200 km, retaining the finer vertical resolution. All of the parameters, such as coefficients for eddy diffusivity and viscosity, are taken to be the same as in SA to demonstrate differences caused only by the difference in resolution. The coefficient of the vertical diffusion is 1.5 cm^2 s^{-1}. In the SA model, the ocean, which extends over the Northern and Southern hemispheres, is forced by cooling in a confined region in the southern part of the Southern Hemisphere and heating in the rest of the ocean through the sea surface.

Figure 1 shows the zonal-mean meridional circulation and zonal averages of zonal flow and density at a steady state for the finer vertical-resolution case, along with those of SA. It should be noted that the horizontal grid size is 100 km. Insignificant changes take place; i.e., almost the same result is obtained for the stacked jets and associated meridional circulation. A slight difference is that the deep water becomes heavier for the finer vertical-resolution case. This is easily understood

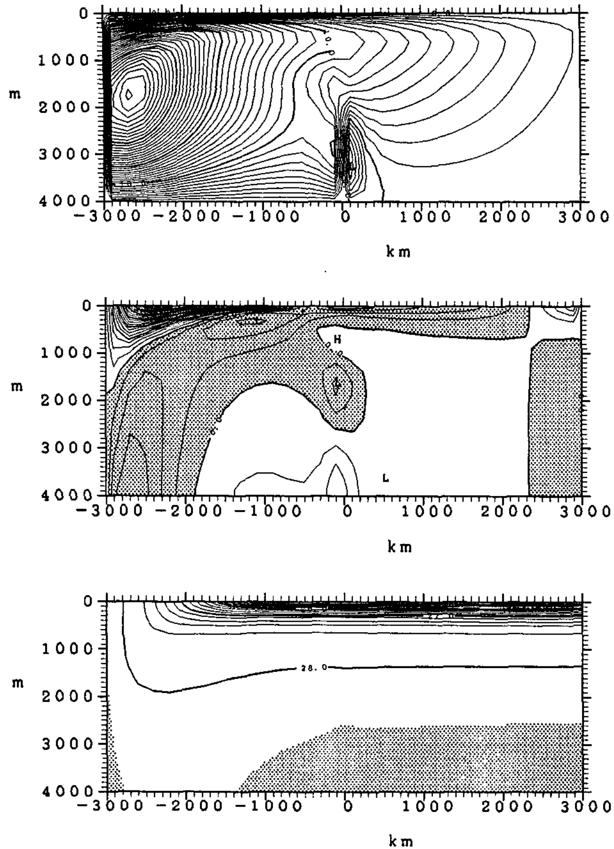

FIG. 2. As in Fig. 1 but for the coarse horizontal resolution case. For the density, the shaded areas indicate σ_t greater than 28.02.

because effects of the computational diffusion caused by the upcurrent scheme depend linearly upon the vertical grid size, and the decrease of the grid size leads to reduction of the computational diffusion.

Figure 2 shows the results for the coarse horizontal resolution. The stacked jets become weaker in speed and the associated meridional circulation changes in pattern. This happens because this feature consists of many vertical higher modes as studied in SA; i.e., the coarse horizontal resolution cannot correctly yield the phenomenon concentrated at the equator.

Now it is substantiated that the stacked jets and associated meridional circulation are realistic features, and it is urgent to go into clarification of details of their dynamics. In conclusion, we would like to emphasize that adoption of the weighted upcurrent scheme may be inevitable at the present state of computing power, because it is not an effective way to satisfy the criterion of the grid Peclet number for the centered difference by taking a very small vertical grid size, say, smaller than 15 m in our model.

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