Reply

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In the preliminary experiment of Manabe and Stouffer (1988; hereafter referred to as MS), which was conducted without the water flux adjustment, the surface salinity over the extensive region of the North Atlantic, including the Greenland–Iceland–Norwegian (GIN) Sea, is very low compared with the modern distribution, preventing the convective production of deep water (see Fig. 5a of MS). In his comments on "Two Stable Equilibria of a Coupled Ocean–Atmosphere System," Birchfield attributes this extensive spreading of fresh water to the excessively large horizontal mixing in the oceanic component of the model used in the MS study. The results from the main experiments of MS, that is, experiments I and II, however, do not confirm this speculation.

In Experiment II, an extensive region of surface water with very low salinity was sustained over the GIN Sea (in a manner similar to the preliminary experiment) despite the large positive in situ adjustment of water flux (see Fig. 8b of MS). On the other hand, the surface salinity is much higher and is close to its modern value in Experiment I using an identical water flux adjustment (see Fig. 8a of MS). Although the large mixing noted by Birchfield should be active in both experiments, the distribution of surface salinity is completely different in the North Atlantic between the two experiments. As we noted, this difference results mainly from the existence or absence of the northward advection of saline surface water in the North Atlantic of the model. In Experiment I, the northward advection of saline water extends all the way into the Norwegian Sea where a relatively high surface salinity is maintained. The North Atlantic surface salinity, however, is very low in Experiment II because of the absence of such advection. Thus, it is not reasonable to blame the excessive horizontal mixing in the model for the extensive surface layer of low salinity in the North Atlantic based upon the results from the experiments in MS.

Birchfield also noted that the Fourier filtering of model variables used for computational stability is also responsible for the excessive smoothing of these fields. The Fourier filter, however, was designed to compensate for the shrinkage of zonal grid size with increasing latitude, and does not make the effective computational resolution of the model in high latitudes less than low latitudes. In fact, the Fourier filter allows 16 zonal waves to be resolved around the latitude circle at 80°N.

We suspect, however, that the failure of the model to maintain the Atlantic thermohaline circulation in the absence of the water flux adjustment is attributable in no small part to the very coarse computational resolution of the model. As noted by Worthington (1970) and Warren (1981), relatively light, saline surface water, which flows northward into the Norwegian Sea, is made dense by strong local winter cooling. The North Atlantic deep water originates from this dense Norwegian Sea water that flows into the North Atlantic over three sills on the ridges connecting Greenland and the British Isles. These overflows entrain the resident North Atlantic water in the course of their descent and join together to form the deep water of the North Atlantic Ocean. To resolve such an intricate circulation, it is obviously necessary to develop a model that has a much higher computational resolution than the model used here. As we noted in MS, the bottom topography of the model was smoothed by removing the unresolvable features. Thus, the height of the ridge was significantly lower, thereby facilitating the exchange of water between the two sides of the ridge. It is clear, however, that the model was incapable of resolving the details of the circulation over the ridge.

One of the important factors that may be responsible for the large adjustment of surface water flux over the GIN Sea is the unrealistically large supply of water through precipitation and runoff over the Arctic Ocean of the model. This is indicated in Fig. 1, which illustrates the original and the adjusted zonal mean fluxes of both liquid and solid water at the ocean surface. The difference between the original and adjusted fluxes indicates the water flux adjustment. Although the magnitude of the zonal mean adjustment at arctic latitudes is much less than the large local maximum of 5 m yr^{-1} cited by Birchfield, it is nevertheless disturbingly large. Figure 1 also indicates that the original water flux is much larger than the observed in high latitudes. This is mainly attributable to the bias of the atmospheric model to exaggerate the poleward moisture transport and, accordingly, the precipitation in these latitudes.

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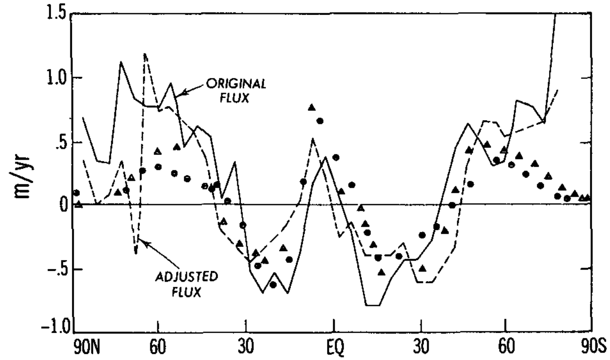

FIG. 1. The latitudinal distributions of the zonally averaged flux of both liquid and solid water (i.e., rainfall, snowfall, and runoff minus evaporation and sublimation) at the surface. Solid and dashed lines indicate the original and adjusted surface water fluxes, respectively. The difference between the two water fluxes represents the zonally averaged adjustment of surface water flux. Units are in meters per year. The estimates of the actual fluxes are indicated by triangles (Peixoto and Oort 1983) and solid circles (Baumgartner and Reichel 1975). This figure is constructed by modifying Fig. A2 (of MS) in which "water flux" indicates liquid water flux (i.e., rainfall plus runoff minus evaporation).

We were encouraged, however, to find that the bias of the atmospheric model toward the excessive arctic precipitation is substantially reduced when the horizontal resolution of the model is doubled.

It appears significant that the adjusted flux is not necessarily closer to the observed flux (illustrated in Fig. 1) than the flux before the adjustment. This result suggests that both the atmospheric and oceanic components of the model have unrealistic bias that should be removed. It is therefore not appropriate to use the terminology "flux correction" in describing our adjustment because it yields a false impression that the flux is correct (or close to the observed) after the adjustment.

In conclusion, substantial increase of the model resolution may be needed to reduce the strong bias of the model toward a halocline catastrophy, that is, the collapse of thermohaline circulation in the North Atlantic Ocean. The nested-grid system proposed by Birchfield is an attractive alternative.

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