Reply

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Koschmieder's main criticism of our experiments with symmetric baroclinic instability (Stone *et al.*, 1969; Hadlock *et al.*, 1972; hereafter referred to as Parts I and II, respectively) is that we have failed to show that the motions we observed are not due to a density circulation or Bénard convection. We did not address this question explicitly in Parts I or II since the characteristic properties we described seemed to us to be remote from those associated with these kinds of motion. In the case of a density circulation, as Koschmieder points out, the meridional motions consist of a single direct cell with rising motions on the warm side of the annulus, and sinking motions on the cool side. The vertical motions we observed have a characteristic horizontal scale much less than the width of the annulus (e.g., see Part I, Figs. 4 and 5, and Part II, Fig. 2) with as many as 13 or 14 meridional cells in series between the inner and outer walls of the cylinder. We do not see how such a motion could be confused with a simple thermally direct density circulation. In the case of Bénard convection a necessary condition for the motions to arise is that the temperature field must be statically unstable. The mean vertical temperature gradients we measured in the region of the observed motions are statically stable (e.g., compare thermistors 2 and 7 in Table 1 of Part II). We do not see how the primary motions under such circumstances can be interpreted as a form of Bénard convection. Evidently Koschmieder has been led astray by the fact that the lower boundary was warmer than the upper boundary. It is well established that the motions that occur in rotating annulus experiments stabilize the fluid so that the static stability in the interior of the fluid is greater than that implied by the temperatures of the upper and lower boundaries (e.g., see Hide, 1967). Only when the lower boundary in our experiments was heated to the point where its temperature exceeded that of the upper boundary by $1\frac{3}{4}$C did motions characteristic of small-scale convection set in (see Part I).

Koschmieder also raises some less important issues. He regards the indirect vertical circulations we found under the most stable conditions as "unusual." It has been well established by both theoretical and experimental studies that this indirect meridional circulation, or Ferrel cell, is characteristic of a baroclinic wave regime [e.g., see Kuo (1956) and Fultz *et al.* (1959)]. Koschmieder implies that the assumptions

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of the stability theory (Stone, 1966) are not valid in the regions where the motions are observed, but does not say how they break down. The only crucial assumptions are that the dominant component of the flow be a zonal thermal wind and that the Taylor number be large compared to unity. As we showed in Part II, these assumptions are valid. Finally, Koschmieder claims that the thermistor readings should have shown a periodic component correlated with the periodic component of the motions. Reference to Figs. 1 and 2 of Part II shows that the spacing of the thermistors was comparable to or greater than the wavelength of the motions. Consequently, they were not capable of resolving a periodic temperature component with the same scale as the motions.

REFERENCES

Fultz, D., R. R. Long, G. V. Owens, W. Bohan, R. Kaylor and J. Weil, 1959: Studies of thermal convection in a rotating cylinder. *Meteor. Monogr.*, **4**, No. 21, 1–104.

Hadlock, R. K., J. Y. Na and P. H. Stone, 1972: Direct thermal verification of symmetric baroclinic instability. *J. Atmos. Sci.*, **29**, 1391–1393.

Hide, R., 1967: On the vertical stability of a rotating fluid subject to a horizontal temperature gradient. *J. Atmos. Sci.*, **24**, 6–9.

Kuo, H-L., 1956: Forced and free meridional circulations in the atmosphere. *J. Meteor.*, **13**, 561–568.

Stone, P. H., 1966: On non-geostrophic baroclinic stability *J. Atmos. Sci.*, **23**, 390–400.

——, S. Hess, R. Hadlock and P. Ray, 1969: Preliminary results of experiments with symmetric baroclinic instabilities. *J. Atmos. Sci.*, **26**, 991–996.