Reply

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Taking each of Dr. Emanuel's points in turn, we shall first comment on his remark about our statement in the abstract of our paper [Orlanski and Ross (1977) hereafter referred to as OR] as to the role of differential advection in a frontal system. This statement is an expression of the effect shown in Eq. (4.4) of OR where the synoptic wind shear is shown to produce the ageostrophic residue $R = fv_z - g\theta_x/\Theta$. By taking the difference between Eqs. (4.3) (multiplied by g/Θ) and (4.2) (multiplied by f), one obtains Eq. (4.4) where the tendency of R results as a consequence of the difference between the horizontal advection terms. In addition, one should recognize that the ageostrophic residue R is the only source for the cross-stream vorticity equation

$$\frac{D\zeta}{Dt} = f\frac{\partial v}{\partial z} - \frac{g}{\Theta}\frac{\partial \theta}{\partial x} = R. \quad (1)$$

This equation as well as Eq. (4.4) in OR were derived only with assumptions of two-dimensionality and inviscid flow and were discussed at length in our paper. The fact that the cross-stream circulation results primarily from the term $(\partial v/\partial x)$ $(\partial U_g/\partial z)$ [assuming the thermal wind relation $(\partial\theta_g/\partial x) \propto (\partial U_g/\partial z)$] as is emphasized by Emanuel in his comments was already recognized in OR as shown in (4.9):

$$\frac{DR}{Dt} = -2f\frac{\partial v}{\partial x}\frac{\partial U_g}{\partial z}. \quad (2)$$

This expression likewise appears in Palmen and Newton (1969, p. 239–240) regarding the enhancement of frontal temperature contrast. Emanuel concludes from the approximate steady-state equation that this term produces the cross-stream circulation. However, we feel that more physical insight can be gained by inspecting the initial development of the circulation and then by recognizing that this term, in general, represents only one means by which an ageostrophic residue can be produced; this residue, in turn, will produce the cross-stream vorticity through Eq. (1). These differences are

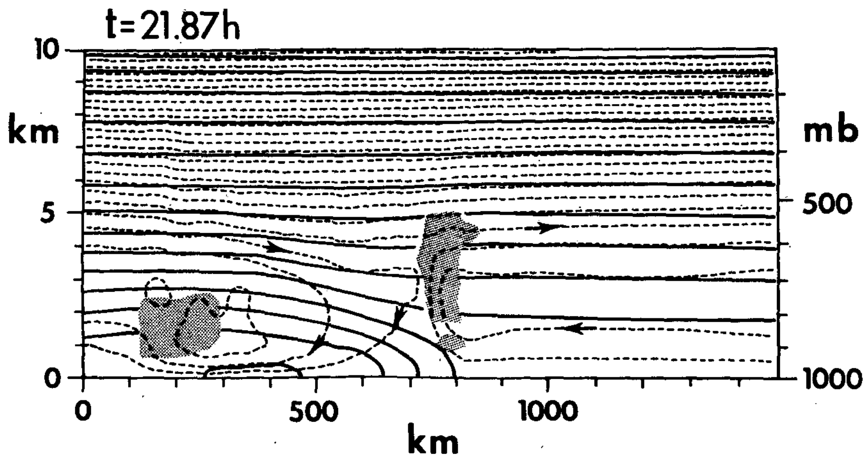

FIG. 1. Figure taken from composite in Fig. 2 of Ross and Orlanski (1978) for the moist surface jet frontal configuration. Solid lines show potential temperature contours. Dashed lines denote streamfunction contours relative to an observer moving with the front. Shaded zones indicate areas of condensed water.

not merely semantic since ageostrophic residues could be generated by other means, e.g., three-dimensional effects or diffusion, and these alternate effects could thereby generate secondary circulations.

Concerning his second point regarding the circulation dependence upon the vertical shear $\partial v/\partial z$, we do not see the relevance of his example to our conclusions. We describe, in detail, the dependence of the secondary circulation on the area of low Richardson number but do not suggest a relationship between the circulation intensity and the vertical shear $\partial v/\partial z$. Emanuel's comments would be more relevant if spatially varying Ri were included in his example where the solution character changes from elliptic to hyperbolic within the domain. After all, the primary results from his example can be seen directly by inspection of his Eq. (1) since, in the limit $\partial v/\partial z \rightarrow \infty$ with the other coefficients remaining constant, $\partial^2\psi'/\partial x\partial z$ and thereby ψ' should be zero over the entire domain.

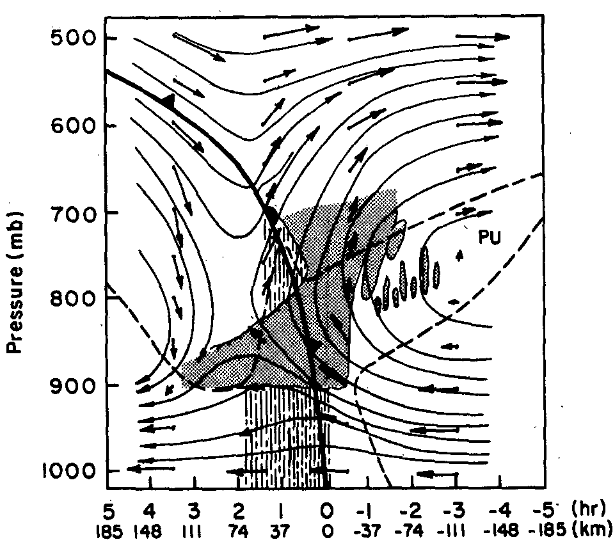

FIG. 2. Figure taken from Fig. 9 of Hobbs *et al.* (1975) showing streamline patterns relative to an observed occluding front in the cross-section plane. Clouds are indicated by stippling and precipitation by vertical hatching.

With regard to the diagnostic equation used by Emanuel, we must point out that a solution of this equation does not guarantee the existence of an equivalent steady-state circulation in nature. In fact, if one changes the sign of the cross-stream synoptic wind shear $\partial U_g/\partial z$ in Emanuel's solution (so as to change the character of his model from an apparent "cold front" to a "warm front" condition), only the sign of the streamfunction expression [his Eq. (2) or (3)] will change, thus indicating a mere reversal of the circulation direction in his solution. However, this result is misleading since OR show in their Fig. 7 that no steady-state circulation is possible for the actual warm front system.

Next we will address Emanuel's comment that "the circulation, in the steady-state, is maintained against dissipation by the conversion of the unlimited amount of available potential energy associated with the temperature gradient along the front." In OR, we have acknowledged the limitation of the two-dimensional approximation that $\partial\theta_g/\partial y$ be held constant. In fact, in the real world, atmospheric fronts are frequently quite two-dimensional, and this available potential energy could be a possible source by which the circulation is maintained over a period of several days.

Finally, although we did not stress in OR the similarities of observed frontal circulations with our idealized results, it is interesting to note the likeness between the circulation (Fig. 1) which developed in a typical moist front solution presented by

Ross and Orlanski (1978) and the observed frontal circulation (Fig. 2) shown by Hobbs *et al.* (1975).

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