Reply

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In response to Das' comments we acknowledge that our analysis (Lipps and Hemler, 1980) is of a theoretical nature, but we contend that it is far from being purely "academic." As indicated in the first paragraph of our study, many important non-reversible effects are not included; however, we see this as no reason why a rigorous discussion of reversible thermodynamics should not be carried out. Indeed, we feel it to be profitable to nail down the relative magnitudes of the more straightforward approximations discussed in our paper before embarking upon an attempted evaluation of the more complex non-reversible effects discussed by Das. It should also be noted that while dr has been set to dr_s, the saturated value in our Eqs. (8), (11) and (13), there is no reason why dr could not be set to some other value as dictated by the appropriate thermodynamics. For example, in our numerical calculations we have used a form of Eq. (13c) which includes the evaporation of rainwater in a subsaturated environment.

In his final comment, Das suggests that the magnitude of each term be displayed as a function of height. Since the terms in (8), (11) and (13) are interacting, we thought it appropriate to plot the behavior of the total equations with height as was done in Fig. 1. There is one comparison not made in our study which is illuminating. That is the direct comparison of Eq. (13b) with the form of Eq. (18) with θ_d replaced by θ, which we have labeled W in Fig. 2. The only difference between these two equations is that W does not contain the liquid water heating term $-c_w w d \ln T$. Thus the comparison of these equations may indicate the importance of this term.

In Table 1 we show the potential temperature difference $\Delta\theta$ between the solutions for W and (13b) as a function of the pressure p_d. The asterisks indicate the values at pressure levels where the temperature is near $-10°C$. This is nominally considered the highest level at which the ice phase is not important in atmospheric clouds. For case I the effective cooling at $-10°C$ by omitting the liquid water heating term is $-0.22°C$ and for case II the corresponding cooling is $-0.62°C$. In case II the cooling is larger because the moisture content associated with the warmer cloud base is larger. The relative cooling of $-0.62°C$ is not considered insignificant. Thus for warm tropical convection or for mid-latitude severe convection where large liquid water loading exists, our analysis indicates that the omission of the liquid water heating may cause significant errors in the thermodynamics.

TABLE 1. $\Delta\theta$ due to omission of the liquid water heating term from Eq. (13b).

Case I		Case II	
p_d		p_d	
900	0	900	−0.001
850	−0.002	850	−0.003
800	−0.010	800	−0.011
750	−0.025	750	−0.024
700	−0.052	700	−0.046
650	−0.095	650	−0.079
600	−0.162	600	−0.131
570*	−0.218*	550	−0.210
550	−0.263	500	−0.331
500	−0.415	450	−0.521
450	−0.635	430*	−0.624*
400	−0.945	400	−0.819
350	−1.360	350	−1.298
300	−1.886	300	−2.055
		250	−3.189
		200	−4.742

* Values near −10°C.

REFERENCE

Lipps, F. B., and R. S. Hemler, 1980: Another look at the thermodynamic equation for deep convection. *Mon. Wea. Rev.*, **108**, 78–84.