# Reply

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We have areas of agreement with the comments of Zhang et al. (1994) (hereafter ZKFG) but we believe their new results raise some of the same questions we addressed previously. Before considering these, we quote the following from our original review (Molinari and Dudek 1992, p. 337): "It should be emphasized that the Fritsch–Chappell approach has been the focus of this section precisely because it has been so successful. No cumulus parameterization has done as well in real-data cases." The intent of the review was to raise doubts about the interpretation of *all* mesoscale model integrations that use cumulus parameterization. We believed, and continue to believe, that insufficient skepticism is being applied by the community as a whole to such results. It was logical in such a review to examine the most successful of the modeling efforts at the time—those of Zhang, Fritsch, and their colleagues. Over the last 14 years they have carried out seminal work in mesoscale cumulus parameterization and in the simulation of mesoscale convective disturbances (e.g., Fritsch and Chappell 1980; Zhang and Fritsch 1987, 1988; Zhang 1989; Zhang et al. 1988, 1989). Our disagreements arise not with the success of their simulations in reproducing observations but in how such simulations are interpreted.

In their new simulations of the PRE-STORM squall line, ZKFG note that the division of detrained water among vapor, cloud, and precipitation did not play a significant role. Although we remain skeptical that detrainment of vapor alone would, under all circumstances, closely match results that included detrainment of precipitation, we look forward to the upcoming manuscript from ZKFG, which will enlarge upon their results.

ZKFG object to our classification system for cumulus parameterizations. With the changes discussed in their section 2b, however, their revised approach now meets our definition of "hybrid," and the distinction does not seem to us to be consequential. As a result, we will leave it to the reader to judge the arguments of ZKFG on the best way to classify approaches and on the efficacy of the original Fritsch–Chappell detrainment procedures. Our response will focus on conceptual issues raised in the original review, which we believe remain valid for the new results shown by ZKFG.

All of ZKFG's successful simulations critically depend upon the development of grid-scale saturation in the lower and middle troposphere in convectively unstable layers, as is apparent from ZKFG's Figs. 3 and 4. Molinari and Dudek (1992, in the abstract) argued that "It is essential to understand the interactions between implicit and explicit clouds that produce this transition, and whether they represent physical processes in nature." Without knowing in detail how the convective parameterization helps to bring about grid-scale saturation in the model, it is impossible to judge whether such evolution occurs for the right reasons.

We have somewhat of a philosophical disagreement with ZKFG on the significance of this issue. ZKFG argue that their results on the resolvable scale are remarkably similar to those observed, and this provides an a posteriori justification of their procedures. In our view, the evolution of the convection from subgrid scale to grid scale in a numerical model arises from delicate balances that can easily go astray. Slight changes in parameter values or initial states could make a significant difference in the results under such circumstances.

Grid-scale moistening in the model arises from surface latent heat flux, evaporation of falling rain, subgrid-scale sources (i.e., detrainment from parameterized convection), and grid-scale vertical advection in the upward motion that occurs in response to convective heat sources. This last term is in essence an artifact of the grid-area averaging process in numerical models. In reality, area-averaged upward mass and moisture fluxes in convective regions (prior to the establishment of mesoscale organization) arise almost entirely from intense *convective*-scale updrafts and downdrafts, which coexist with weak between-cloud vertical motions. [See, for instance, the cloud ensemble model re-

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sults of Soong and Tao (1980).] One role of cumulus parameterization is to offset grid-scale upward moisture transport with (parameterized) convective drying in order to simulate a realistic evolution of relative humidity on the grid. The net grid-scale moistening is the small difference of the two large terms. This is especially true in the lower and middle troposphere, where convective moistening by detrainment is likely to be small, and convective drying to be large.

The implications of this are significant for mesoscale cumulus parameterization. In the ZKFG approach, convective forcing is fixed for 30 min to 1 h while the grid scale continues to evolve. This procedure could easily disrupt the delicate balance between grid-scale vertical advection of moisture, which is likely to increase with time in response to the parameterized heating, and convective moisture sinks, which are fixed. Such circumstances could easily result in grid-scale saturation. If this were so, the critical development of saturation would not seem to be based on any physical process in nature.

A moisture budget from the model output could address these issues, but relative humidity tendencies would be much more meaningful than the specific humidity tendencies shown in Fig. 1 of ZKFG. In addition, both grid-scale and convective contributions need to be shown to describe the process. The results shown in Fig. 1 of ZKFG are unsatisfying in this regard. It remains impossible to determine whether grid-scale saturation occurs due to imbalances arising purely from procedural aspects of the model physics.

These comments may seem overly demanding of the details in a 25-km grid mesh model. That, however, is precisely the point: a 25-km mesh model can accomplish only so much. We contend that the *process* by which individual cumulonimbus clouds develop mesoscale organization remains poorly understood, despite the many excellent simulations of Zhang, Fritsch, and their colleagues. The reason is that, again quoting Molinari and Dudek (1992, p. 341), "In such models, it is not possible to understand the *interaction* of the convective scale and mesoscale, because cumulus parameterization fixes that interaction a priori through closure conditions." A parallel exists in hurricane simulations. Early numerical models produced reasonably realistic mature hurricanes, but no one would now argue that the process by which the model hurricanes reached the mature stage was like that in nature [for the latter, see Emanuel et al. (1993)]. This point has been eloquently made by Ooyama (1982). The simulations of Zhang et al. (1988, 1989, 1994) may provide considerable insight into the mature squall line or mesoscale convective complex, but we believe they are of less value in understanding the development of such features.

As with our previous comments, these are not at all intended to belittle the many remarkable simulations and genuine achievements of Zhang, Fritsch, Kain, and their colleagues. Rather, we simply argue that great caution be exercised in interpreting such results, especially with regard to the physical and dynamical effects of cumulus convection. Mesoscale convective systems will likely require simulation with cloud-model-scale resolution (without cumulus parameterization) before complete understanding of their life cycle can be achieved.

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