where α represents one of the model's variables, and $\hat{\alpha}$ is a variable that has been time-filtered. A time filter is necessary with leapfrog integration to prevent the model's three time levels from diverging. MM5 uses an Asselin (1972) filter, where the three time levels are averaged as follows:

$$\hat{\alpha}^t = 0.1\,\hat{\alpha}^{t-\Delta t} + 0.8\,\alpha^t + 0.1\,\alpha^{t+\Delta t} ,$$

This practice is common to many atmospheric models, from cloud models to climate models.

We have found that the Asselin filter is a source of the θ_e problem. Note that if a variable is increasing in time at a linear rate, $\hat{\alpha}$ will be equivalent to α, i.e., the value will be unchanged by the time filter. However, most meteorological fields change non-linearly in time, so the Asselin filter typically alters the value of α (but usually only slightly). In the case of a rapidly growing cumulonimbus cloud, thermodynamic variables (such as temperature, T, and mixing ratio, q_v) are exponentially increasing in time at grid points in the path of the ascending cloud. Therefore, the application of a time filter artificially increases T and q_v *every time step* in regions of cloud growth. As an example, consider the following values of T:

$\hat{T}^{t-\Delta t}$	T^t	$T^{t+\Delta t}$	$\hat{T}^t$
280.0	280.5	281.3	280.53

Notice that temperature increased by 0.5 K during the first time step, and by 0.8 K during the second time step. The value of $\hat{T}^t$ (i.e., after application of the Asselin filter) is 0.03 K higher than the original value (T^t). Water variables (such as q_v) are artificially increased in the same manner. Since both T and q_v increase in this manner, the θ_e is artificially increased every time step. Through the positive feedback mechanism described in the previous section, the θ_e problem can quickly produce extremely unrealistic values.

Because the time filter is applied to T, q_v, and pressure separately, the procedure upsets the 100% relative humidity assumption. Clark (1979) recognized this fact, but reported that there was no "significant effect" on his simulations.

In the ARPS model, a forward-in-time (FIT) scheme is available for integrating the temperature and moisture variables (using flux-correcting transport for advection). With FIT integration, a time filter is not necessary. Using this scheme in ARPS significantly reduces the θ_e problem (see Table 1). In fact, when using ARPS with FIT integration and our iterative condensation closure (see section 3.1), the θ_e problem is eliminated.

4. CONCLUDING REMARKS

Evidence has been presented to document artificial increases in θ_e during cloud-scale ($\Delta x \le 4$ km) thunderstorm simulations. Typically, the θ_e problem is more prevalent for rapidly growing clouds. It is important to recognize that the initialization of the clouds in these experiments (using a warm bubble) results in a very rapidly growing thunderstorm. Real data experiments typically produce slower evolving storms, so assuming the model contains sufficient mixing, the θ_e problem may not always appear. Furthermore, note in Fig. 1 that the θ_e problem may only appear for short periods of time, and can be missed even with output every 10 minutes.

We are continuing to investigate the effect of the θ_e problem on simulations of thunderstorms. The total amount of condensation and, therefore, the amount of surface precipitation are substantially increased in simulations that have the θ_e problem. This result further highlights the challenge of cloud-scale quantitative precipitation forecasting.

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