5.2 MESOSCALE PROCESSES ASSOCIATED WITH RAPID EROSION OF THE "CAP"

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1. INTRODUCTION

The development of deep convection depends on the existence of Convective Available Potential Energy (CAPE). Yet, in most environments with CAPE, there is a layer of negative buoyancy, or convective inhibition (CIN), that parcels must overcome before they can respond to CAPE. Over certain regions of the world, such as the Great Plains of the U. S., both CIN and CAPE can become quite large. Under these circumstances, forecasters commonly note that severe convection may develop if the “cap” can be broken, i.e., if the CIN layer can be weakened to the point where underlying parcels can penetrate through to the layer of large positive buoyancy.

Predicting whether the cap will be broken can be quite challenging. Part of this challenge arises from the fact that several physical processes have the potential to erode this stable layer. For example, horizontal temperature advection, temperature changes associated with vertical motion, and evaporative cooling associated with precipitation falling from above can all act to change cap strength. Yet, it is usually very difficult to isolate the impact of these individual processes, even in retrospect.

In this study, we examine erosion of the cap from a quantitative perspective, focusing on the Norman, Oklahoma (OUN) sounding observed at 1200 UTC on 22 April 2001. The cap that existed in this sounding eroded rapidly during the ensuing 6 hours, as revealed by a special 1800 UTC raob from OUN. A forecast sounding from an experimental version of the Eta model, run over the same time period, captured the observed 1800 UTC vertical structure quite well. Furthermore, the model also predicted scattered light rain showers during this period, consistent with observations. This consistency suggests that the model may provide us with a window of insight into the complex physical processes leading to the cap erosion.

The cap erosion process is examined by extracting model temperature tendencies associated with all physical processes during the 6h forecast from 1200 to 1800 UTC. The operative physical processes are identified and quantified using these temperature tendencies and other diagnostic calculations.

2. SYNOPTIC SCALE AND MESOSCALE SITUATION

An active spring pattern was in place across the southwestern and central U.S. on the morning of 22 April 2001 with a deep upper trough and closed low situated near the Four-Corners region and a broad belt of southerly low level flow (25-30 m/s at 850mb) from south Texas into the Central Plains. Persistent midlevel southwesterly flow in advance of the upper trough had resulted in the advection of a pronounced elevated mixed layer airmass (marked by very steep lapse rates in the 700-500 mb layer) eastward and northeastward across the Southern Plains. This layer was quite evident on morning soundings and resulted in significant capping of the moist boundary layer and strong CIN (Fig. 1).

At the surface (not shown), a 994 mb low center was located over southeastern Colorado with a strong cold front evident in the thermal analysis from the low center south across eastern New Mexico. Pronounced low-level cold air advection was occurring to the east of the Front Range and across northeast Colorado, while a strong warm front was situated from northwest Kansas eastward along the Kansas/Nebraska border. As the upper trough and surface low developed northeastward across the Central Plains through the day, strong flow in the base of the upper trough (45 m/s at 500mb) aided in the rapid eastward translation of the surface dry line and cold front from eastern New Mexico eastward across Kansas, Oklahoma, and north Texas.

This pattern is not unusual for the Plains during the spring and the potential for severe weather associated with this system was highlighted by the Storm Prediction Center (SPC). However, the presence of the strong cap did produce considerable uncertainty in the SPC forecasts, as revealed in this part of the convective outlook forecast forecast discussion:

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...THIS SHOULD ENHANCE INSTABILITY WITH 1500-2000 J/KG SBCAPE ON FORECAST SOUNDINGS. **MID LEVEL STABLE LAYER --EFFECTIVE CAP --MAY RESULT IN MORE OF A SEGMENTED STRUCTURE TO CONVECTIVE LINE.** STRONG VERTICAL SHEAR PROFILES FROM REGIONAL VWP/PROFILER DATA SUPPORT DISCRETE SUPERCELLS AND TORNADO RISK WITH MAIN LINE IN ADDITION TO BOW ECHOES. 200-400 J/KG SRH AND 40-50 KT SURFACE-6 KM SHEAR OBSERVED AT FDR...FOR EXAMPLE. **HOWEVER CONVECTIVE POTENTIAL AHEAD OF MAIN LINE SHOULD BE LIMITED BY STRENGTH OF CAPPING.**

Because there was some uncertainty regarding cap strength and persistence, special 1800 UTC soundings were launched at selected locations. The sounding from OUN showed that dramatic cooling and moistening had occurred in the layer around 700 mb since 1200 UTC (Fig. 1). Supplemental upper air soundings from a number of other Great Plains locations also revealed cooling near this level. Since scattered light rain showers had fallen in this region between 1200 and 1800 UTC, our initial hypothesis was that evaporative cooling associated with rain falling through the elevated mixed layer played a significant role in the elimination of the cap over central Oklahoma.

3. MODEL OUTPUT AND ANALYSIS

On this day forecasters used both the operational Eta model (Black 1994) and an experimental version of the Eta run at NSSL (see Kain et al. 2003; hereafter EtaKF). In the 1200 UTC run of the Eta, parameterized deep convection activated over OUN well before the 1800 UTC forecast time, causing model-output soundings to conform to the smooth, nearly moist adiabatic profiles (Baldwin et al. 2002) associated with the Betts-Miller-Janjic convective scheme (Janjic 1994). These soundings were quite different from the observed 1800 UTC sounding (Eta soundings not shown). In contrast, the EtaKF run did not activate deep convection before this time, but it did generate light (grid-resolved) precipitation upstream from OUN, consistent with observations of light rain showers across portions of southwestern Oklahoma. Furthermore, the EtaKF's 6 h forecast of the OUN sounding structure showed quite good agreement with the observed OUN sounding (Fig. 2).

Although rapid and unexpected cap erosion occurs perhaps several times a year over the Great Plains, our experience suggests that forecast models usually do not simulate this process well. Thus, the consistency

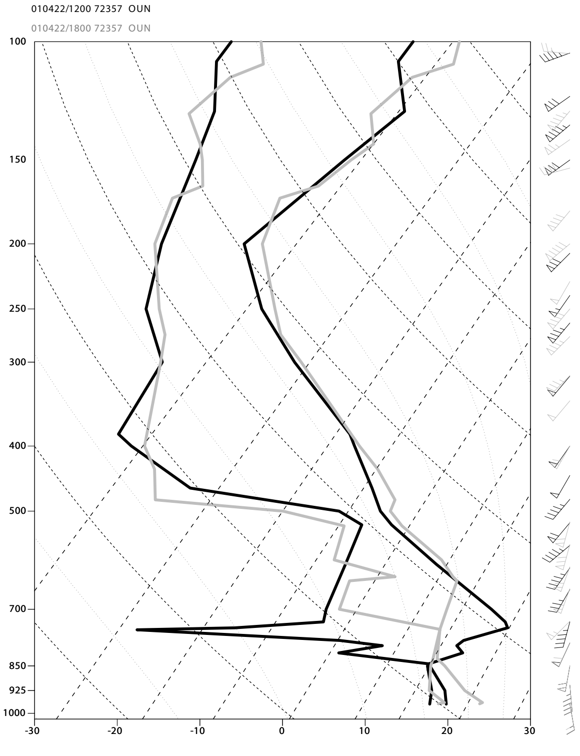

Fig. 1. Observed upper air soundings from Norman, OK (OUN) 22 April 2001 at 1200 UTC (black) and 1800 UTC (gray).

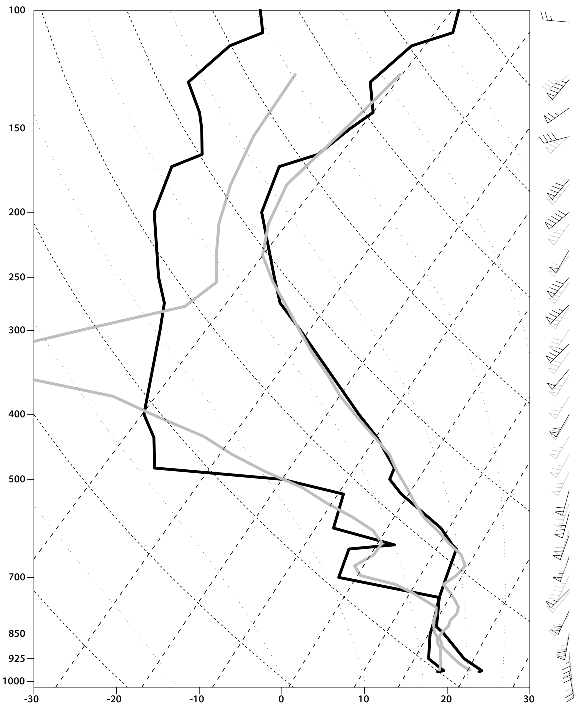

Fig. 2. Observed (black) and EtaKF forecast (gray) soundings valid 1800 UTC 22 April 2001.

between model and observations in this case provides us with a rare opportunity to use the EtaKF as a surrogate for the real atmosphere and to diagnose the mesoscale processes responsible for the cap erosion in the model, with obvious inferences for the real atmosphere.

Extracting tendencies associated with different physical processes is one way of assessing the relative importance of each process in a model (e.g., Kain et al. 2000). For the EtaKF forecast, we found that temperature changes associated with vertical motions, grid-resolved latent heating, and horizontal advection dominated the total temperature tendency over central Oklahoma during the first 6 h (i.e., from 1200-1800 UTC). The temporal evolution of these tendencies over OUN is revealed in Fig. 3. The largest tendencies occurred between the 1 and 3 h times (1300 – 1500 UTC), when a weak elevated disturbance moved through the area, inducing upward motion, condensation, and precipitation formation aloft. The upward motion is implied by the cooling due to vertical motions[1], peaking at about 475 mb just after the 2 h time (Fig. 3a). This period of upward motion is associated with a maximum in latent heating (Fig. 3b). The precipitation generated by this disturbance evaporated as it fell through the relatively dry elevated mixed layer between about 650 and 800 mb, introducing fairly strong latent cooling over the same time period (Fig. 3b). This cooling appears to have induced sinking motion in the model environment, reflected by a period of subsidence warming that lags slightly behind the evaporative cooling (Fig. 3a). Over the same period, temperature tendencies due to horizontal advection are comparable in magnitude to the other terms (Fig. 3c). Notably, all three terms have maximum absolute values around 720 mb, near the “nose” of the cap (Fig. 1).

The relative magnitudes of these terms can be seen more clearly by focusing on the 720 mb level (Fig. 4a). An extended period of net cooling begins just before the 1 h time (1300 UTC), due initially to a combination of upward motion and horizontal advection. Shortly there-

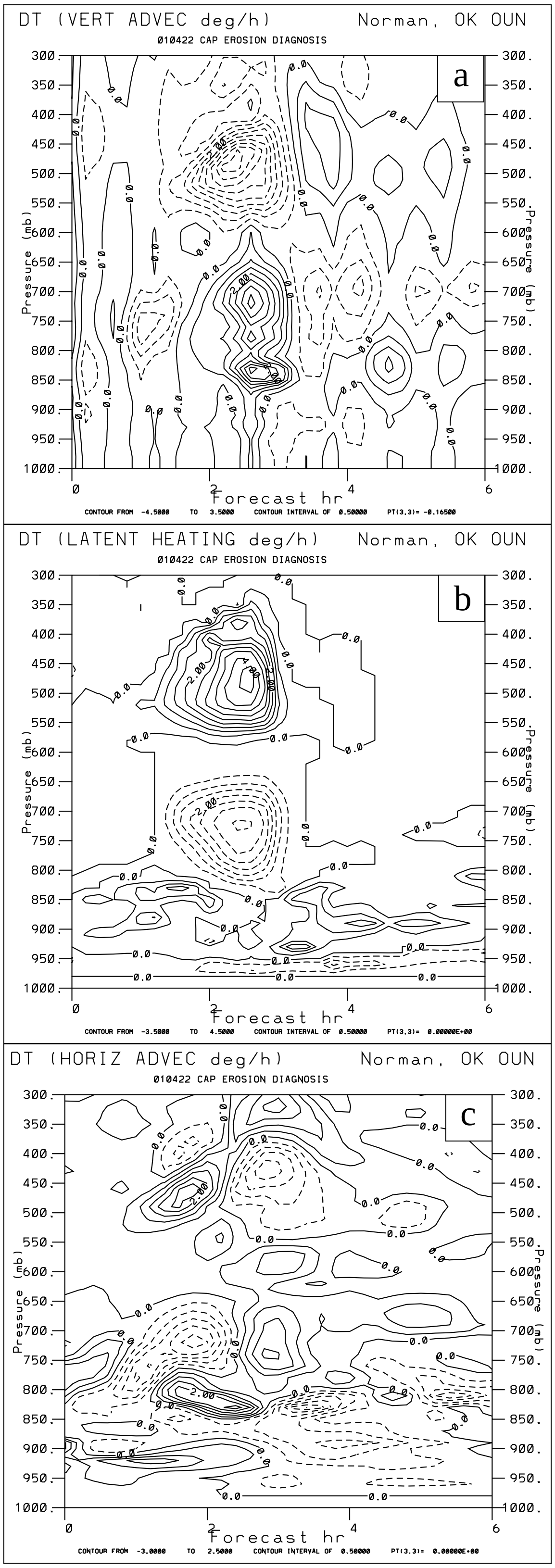

Fig 3. Temperature tendencies (contour interval = 0.5 K h^{-1}; dashed lines indicate negative values) from a 6 h forecast of the EtaKF in a time-height cross section at OUN due to a) vertical motions, b) grid-scale latent heating, and c) horizontal advection.

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[1] In this study, the phrases temperature changes due to “vertical motions” and/or “vertical advection” are used synonomously to denote the combined effects of vertical advection and adiabatic temperature changes due to compression/expansion, as given by $\frac{\partial T}{\partial t} = -w(\Gamma_d - \gamma)$, where T is temperature (K), t is time (s), w is vertical velocity ($m\ s^{-1}$), Γ_d is the dry-adiabatic lapse rate ($K\ m^{-1}$), and γ is the actual lapse rate ($K\ m^{-1}$).

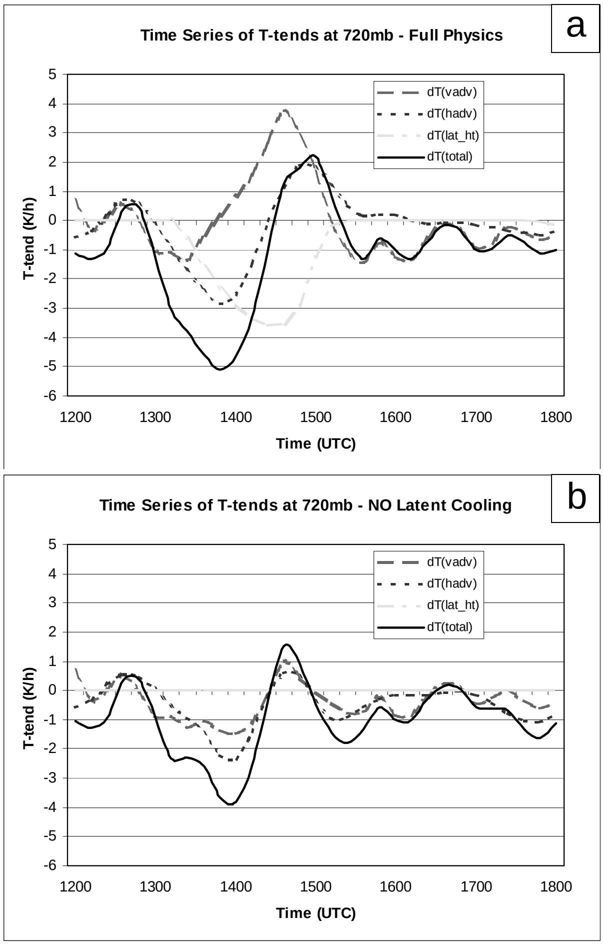

Fig. 4. Time series of temperature tendencies (K h^{-1}) at 720 mb due to vertical motions (dT(vadv)), horizontal advection (dT(hadv)), grid-scale latent heating/cooling (dT(lat_ht)), and the total temperature tendency for 6 h EtaKF forecasts with a) normal (i.e., full physics) configuration, and b) no grid-scale latent cooling.

after, evaporative cooling commences and eventually becomes the largest negative term in the net (total) temperature tendency. Yet, it appears to be slightly out of phase with the net tendency. In contrast, subsidence warming (dT(vadv)) appears to phase quite well with evaporative cooling (dT(lat_ht)). Furthermore the subsidence effect is nearly equal in magnitude to the evaporative cooling, so that it effectively offsets it. Meanwhile, the horizontal advection term (dT(hadv))appears to be very closely phased with the total temperature tendency.

Our initial hypothesis was that evaporative cooling played a significant role in eroding the cap. The above analysis showed that this term was indeed the largest negative contributor to the net temperature tendency. Yet, it appeared to be offset by subsidence warming and it was out of phase with the net tendency. The role of horizontal advection was also puzzling. Analysis of upper air data at 1200 UTC showed that prevailing wind patterns should produce *warm* advection within the elevated mixed layer, i.e., it was *warmer* upstream (to the southwest). Could it be that evaporative cooling upstream cooled the air as it was being advected towards OUN?

In response to these questions and concerns, the model was rerun with all latent-cooling effects “turned off”, i.e., all negative latent heating effects were set to zero during the model integration. In this run, the total temperature tendency still oscillates between the 1 and 3 h times, but the magnitude of the oscillation is smaller than in the “full-physics run” (Fig. 4b). The cooling tendency from the horizontal advection term is only slightly weaker, suggesting that upstream evaporative cooling did not play an important role in determining the character of horizontal advection. However, the tendencies due to vertical motions are very different. In particular, weak cooling due to upward motion persists beyond the 2 h time (1400 UTC) and the strong peak in subsidence warming that occurred between the 2 and 3 h times (1400 and 1500 UTC) is sharply reduced in both amplitude and duration. The dramatic changes in subsidence warming appear to confirm our suspicion that much of the subsidence warming in the first run occurred as an

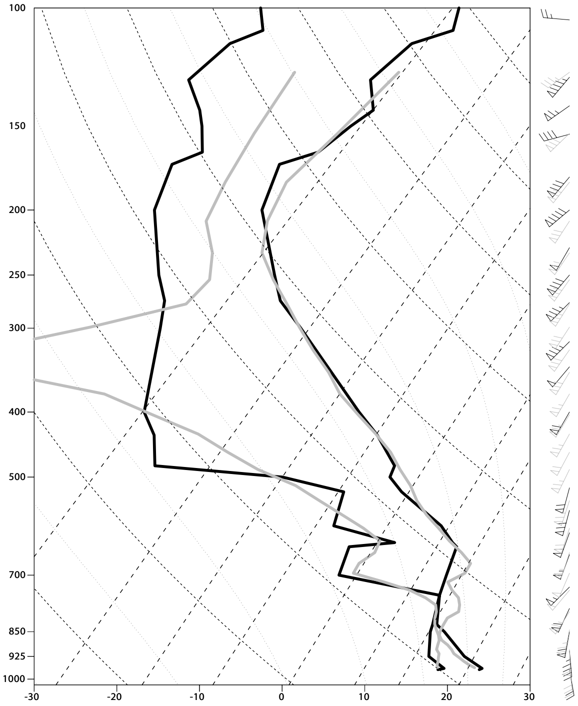

Fig. 5. Observed (black) and EtaKF forecast (gray) soundings valid 1800 UTC 22 April 2001. Latent cooling was not allowed in this run of the EtaKF.

environmental response to negative buoyancy induced by evaporative cooling – evaporative cooling is largely offset by subsidence warming.

Perhaps the biggest surprise from the no-latent-cooling run was in the structure of the model forecast soundings. The 6 h (1800 UTC) model sounding at OUN *still* showed remarkably good agreement with observations (Fig. 5), *and* with the sounding from the original model forecast (cf. Figs. 2 and 5). This result suggests that evaporative cooling produced only a transitory effect on the structure of the cap in this case and that horizontal advection of cooler air was the primary agent of cap erosion.

An important question that remains is, how did prevailing wind fields bring in colder air aloft when the initial temperature gradient was directed downstream? Detailed analysis of model fields and temperature tendencies, including vertical cross sections parallel to the mid-level flow (not shown), reveal that a broad region of lower-to-middle tropospheric upward motion developed shortly after 1200 UTC over southwestern Oklahoma. This process cooled the upstream air and reversed the initial temperature gradient so that ambient wind fields brought in cooler air in the layers where convective inhibition was the largest at 1200 UTC. Work is underway to understand the dynamic process that induced this upstream rising motion.

4. SUMMARY AND CONCLUSION

Observed soundings from Norman, Oklahoma (OUN) showed a rapid erosion of the “cap” between 1200 and 1800 UTC on 22 April 2001. Shortly thereafter, severe convection developed in the area. In this case, both the sounding structure and the deep convection were well forecast by the EtaKF, an experimental version of the Eta model run at NSSL. This model forecast was used to diagnose the physical processes associated with elimination of the CIN layer in the model, in the hope that this analysis will help us to better understand and forecast cap erosion in the real atmosphere.

Since light rain showers were observed (and forecsted by the model) near and upstream from OUN during the period in question, our original hypothesis was that evaporation played an important role in cooling and moistening the dry stable layer near the nose of the cap. Temperature tendencies extracted from the model showed that evaporative cooling was the largest negative contributor to the total temperature tendency at this level. Yet, the evaporation seemed to induce subsidence and the warming associated with this sinking motion essentially offset the evaporative cooling. The strong subsidence warming did not develop in a second model run with latent cooling “turned off”. Furthermore, the 6 h (1800 UTC) OUN forecast sounding from this second run was almost identical to the sounding from the first run. This strongly suggests that evaporative cooling was not the operative process in the rapid cap erosion.

Further analysis of model showed that horizontal advection was the primary agent of cooling within the CIN layer over OUN. This process was discounted in our preliminary analysis because the initial temperature gradient was directed downstream. However, it appears that upward motion developed over a mesoscale area upstream of OUN just after the 1200 UTC time. This process cooled the air in the CIN layer and reversed the temperature gradient, allowing prevailing winds to advect cooler, moister air over OUN.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Baldwin, M. E., J. S. Kain, and M. P. Kay, 2002: Properties of the convection scheme in NCEP's Eta Model that affect forecast sounding interpretation. *Wea. Forecasting*, **17**, 1063-1079.

Black, T.L., 1994: The new NMC mesoscale Eta model: Description and forecast examples. *Wea. Forecasting,* 9, 265-278.

Janjic, Z.I., 1994: The step-mountain eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes. *Mon. Wea. Rev.*, **122**, 927-945.

Kain, J. S., S. M. Goss, and M. E. Baldwin, 2000: The melting effect as a factor in precipitation-type forecasting. *Wea. Forecasting*, **15**, 700-714.

Kain, J. S., M. E. Baldwin, and S. J. Weiss, 2003: Parameterized updraft mass flux as a predictor of convective intensity. *Wea. Forecasting,* **18***,* 106-116.