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OBSERVATIONS OF COLD POOL PROPERTIES IN MESOSCALE CONVECTIVE SYSTEMS DURING BAMEX

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1. INTRODUCTION

Several numerical modeling studies have identified the surface-based cold pool as a critical factor in the organization of deep precipitating convection (e.g., Thorpe et al. 1982; Rotunno et al. 1988; Fovell and Ogura 1989; Szeto and Cho 1994; Trier et al. 1997; Parker and Johnson 2004). However, direct observations of cold pools have been limited, due to the sparsity of the operational rawinsonde network in space and time. In particular, the evaluation of theories based on numerical models requires observations near the leading edge of a mesoscale convective system (MCS), preferably within the MCS convective region; this area is rarely measured, and usually not with the operational network.

The Bow Echo and MCV Experiment (BAMEX) was designed partly to address this observational void. During BAMEX, about 700 soundings were obtained using mobile ground-based and airborne research platforms. Almost all soundings were within or near MCSs, or within mesoscale vortices generated by MCSs. Thus, the sounding data collected during BAMEX provide a unique opportunity to evaluate the properties of the cold pools within MCSs.

2. METHODOLOGY

2.1 Data

This study uses the BAMEX composite sounding dataset interpolated to constant 5 mb levels, provided by the Joint Office for Science Support (JOSS). Documentation for this dataset is available at the JOSS web site http://www.joss.ucar.edu/bamex/dm/archive. This dataset includes all available atmospheric soundings, including dropsondes from the Learjet, rawinsondes from mobile ground-based platforms (MGLASS), and rawinsondes from the NOAA operational network.

Surface observations are obtained from the same JOSS database. Whenever possible, our analyses utilize 1-min ASOS observations. When these data are not available, we use the standard surface observations (i.e., regular hourly observations, plus any special reports).

We use radar images derived from the WSI NOWrad product on a 2 km grid with 15 min temporal resolution. These data are used to determine overall MCS structure (e.g., trailing stratiform versus leading stratiform). They are also used to determine MCS propagation speeds by tracking the movement of the convective region over several hours.

2.2 Sounding selection

To determine the intensity of MCS cold pools, two soundings are required: one that is representative of the environment; and one that samples the cold pool of the MCS. Different criteria are used to select these two classes of soundings.

For the environmental sounding, the sonde must have sampled the low-level air that comprised the inflow to the system. Fortunately, many environmental soundings were available to choose from, most of them within 100 km of the convective line, and < 2 h before system passage. For this initial investigation, one environmental sounding is chosen for each of the cold pool soundings; no attempt is made at this time to measure possible heterogeneity in the environment.

The cold pool soundings are initially selected if they probably sampled the convective cold pool. This selection is based on subjective comparisons of sonde location, system movement, and system structure. The list of candidate soundings is further reduced by examination of the soundings themselves; a case is excluded if it appears to contain observational errors, or if the sounding does not contain sufficient data for analysis. Finally, for this paper, we include only those cases that sampled the mature stage of MCSs with trailing stratiform regions. The final list for the analyses herein contains 15 cold pool soundings from 7 IOPs.

This methodology contains considerable uncertainty, even considering the excellent spatial and temporal resolution of the BAMEX dataset. In particular, it is important to note that each sounding represents *local* conditions that are not necessarily representative of the entire MCS.

2.3 Analysis methods

Cold pool intensity is measured by *C*, defined herein by

$$C^2 = -\frac{2}{\overline{\rho}(z=0)}\int_0^H \left(\overline{\rho}B\right)dz\ , \qquad (1)$$

where z is height, H is the cold pool depth, ρ is density, and B is buoyancy,

$$B = g\left(\frac{\theta-\overline{\theta}}{\overline{\theta}} + 0.61\left(q_v - \overline{q}_v\right)\right). \qquad (2)$$

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In (2), g is the gravitational acceleration, θ is potential temperature, and q_v is water vapor mixing ratio. Overbars indicate environmental conditions, from the environmental sounding, and all other calculations are based on the cold pool sounding. The effects of frozen and liquid hydrometeors on B are necessarily neglected, because these quantities are not available from the soundings. The value for H is the height above ground at which B is first observed to be 0 m s^{-2} (i.e., the approximate top of the cold pool).

The formulation for C, (1), is slightly different from the standard definition because of the inclusion of ρ inside the integral. This definition results from a preliminary derivation based on the deep anelastic equations. In contrast, the standard derivation (e.g., Rotunno et al. 1988) utilizes the Boussinesq equations, which are only valid for very shallow fluids (H << the density scale height, which is about 8 km). We show in the next section that cold pools during BAMEX were often very deep (i.e., H > 4 km); the Boussinesq assumption is tenuous for these depths. Furthermore, Trier et al. (2005) found that (1) better explains numerically simulated MCS propagation when applied from the surface to the stratosphere. When (1) is integrated beyond $z = H$ to include the effects of the warm anomaly aloft, a deep anelastic definition is definitely required. When applied only to the cold pool, the use of (1) instead of the standard Boussinesq formulation typically reduces C by up to 10%.

A measure of the potential temperature difference ($\Delta\theta$) across the gust front at the surface is obtained from surface observations. For all cases, we choose a surface site that is closest to the location of the cold pool sounding. The time series for that station is analyzed, and the maximum potential temperature difference is recorded, following the methodology of Evans and Doswell (2001).

All winds and propagation speeds in this paper are reported in a reference frame along the axis of MCS movement. The surface wind component toward the MCS (u_{sfc}) is obtained from surface observations by averaging all available observations for the 2-h period before passage of the gust front.

3. COLD POOL DEPTH AND INTENSITY

All analyses of mature, trailing stratiform MCSs during BAMEX for which there are sufficient observations indicate cold pools that are deep (H > 3 km) and intense (C > 20 m s^{-1}) (Fig. 1). In fact, more than half of the cases had H > 4 km. In many cases, H was close to the melting level, suggesting a possible role of melting in creating such large values for H and C, which are larger than those reported in many idealized numerical modeling studies.

The large values for C and H were unexpected, and have raised some concerns by our colleagues about the accuracy of the data. Based on additional analyses, we

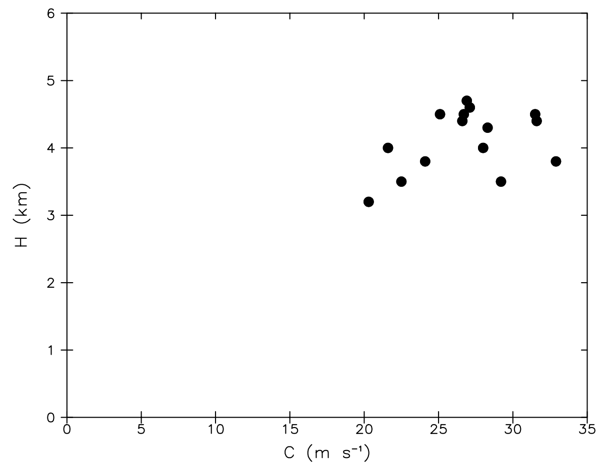

Fig. 1. Values of C and H for 7 mature, trailing stratiform squall lines (15 observations).

believe the calculations are truly representative of the MCSs observed during BAMEX. The discrepancy between these analyses and past work is probably attributable to the types of environments that occurred during BAMEX. For example, the environment ahead of the IOP7 bow echo has a deep (> 200 mb), elevated dry adiabatic layer, starting ~200 mb above the surface (Fig. 2a). Environmental soundings such as this are not typically studied in idealized numerical modeling work.

The cold pool sounding for this case reveals a nearly isothermal layer near the melting level, with approximately moist adiabatic layers just above and below the melting level (Fig. 2b). Such isothermal layers can occur in the presence of intense melting. This is the sharpest isothermal layer observed during BAMEX. Most of the other cold pool soundings exhibit nearly moist adiabatic layers near the melting level.

The resulting vertical profile of B derived from these two soundings shows that a 3.8 km layer has been cooled, yielding C = 33 m s^{-1} (Fig. 3). The height where B = 0 (i.e., at ~650 mb) is within the elevated dry adiabatic layer. Thus, it seems that this type of environmental sounding can be cooled over a deep layer, as demonstrated recently by Bukovsky et al. (2005, e.g., their Fig. 8).

Also of interest in Fig. 3 is the fact that B decreases with height in the lowest ~3 km, and has a maximum value at ~700 mb. This is also different from most idealized modeling studies, which often show the minimum value for B at the surface. In fact, the surface potential temperature difference ($\Delta\theta$) in these two soundings is only 3.8 K. The small difference in surface buoyancy between the cold pool and the environment is partially attributable to low-level nocturnal cooling in the environment.

Two recent studies (Evans and Doswell 2001; Stensrud et al. 2005) proposed that $\Delta\theta$ might provide a good estimate for C. A reliable proxy for C using only surface

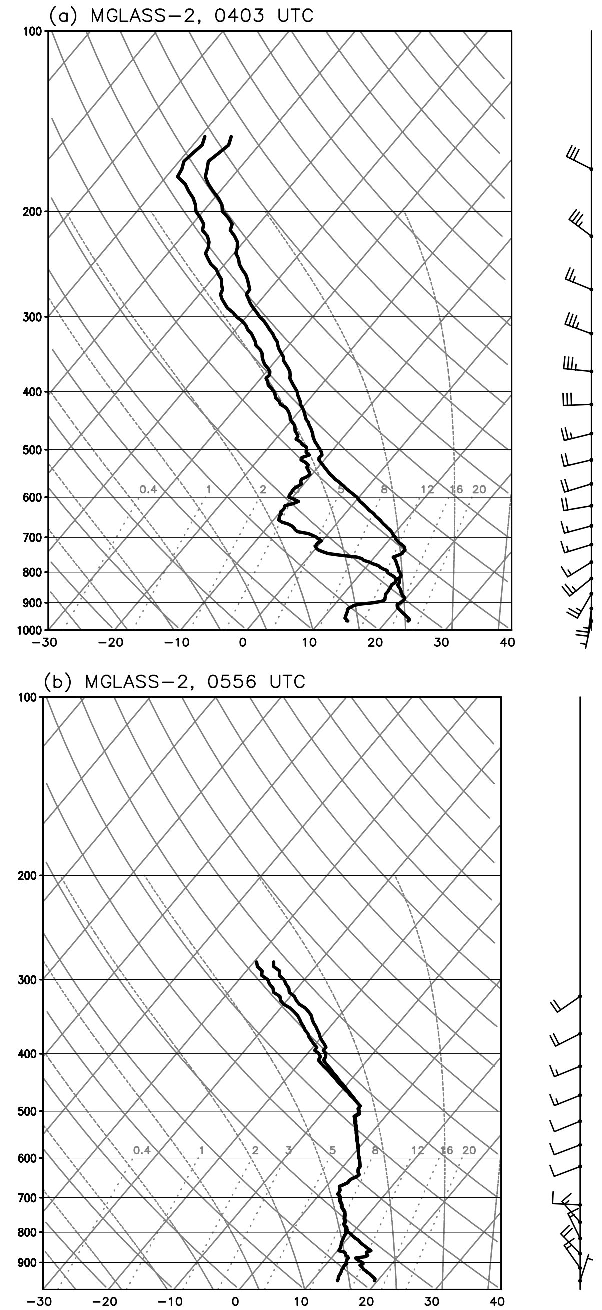

Fig. 2. Soundings from MGLASS-2 on 10 June 2003 at (a) 0403, and (b) 0556 UTC.

observations would be useful, given that C is difficult to calculate from conventional datasets. However, an analysis of $\Delta\theta$ compared to C from the BAMEX observations does not support a useful relationship between $\Delta\theta$ and C (Fig. 4). For half of the BAMEX cases, the relationship proposed by Stensrud et al. (2005), which was derived from numerical simulation, underpredicts C by more than a factor of 2. We feel this poor correlation between C and $\Delta\theta$ should be expected, because C is a vertically integrated measure, whereas $\Delta\theta$ only reflects differences at the surface. Our analysis of the BAMEX

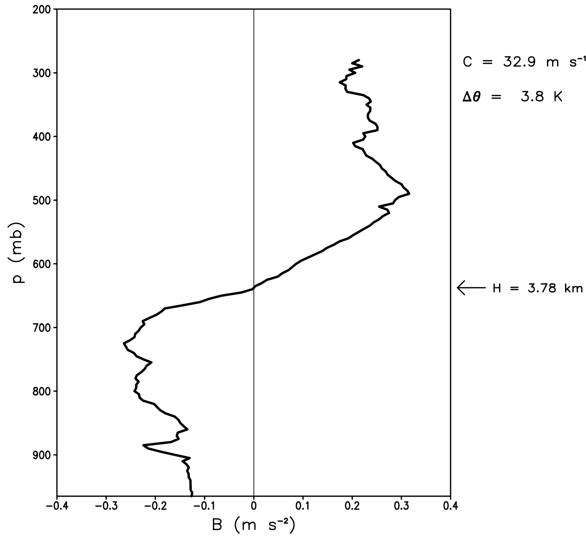

Fig. 3. Vertical profile of buoyancy calculated from the two soundings in Fig. 2.

cases reveals that differences in low-level stratification in both the environment and in the cold pool can strongly effect calculations of C, even for cases that have similar values for $\Delta\theta$. We surmise that the numerical simulations of Stensrud et al. (2005) did not vary the low-level stability in the environment, at least not to the extent that is typical in the low-levels of observed MCSs.

4. MCS PROPAGATION

Theoretically, C predicts the propagation speed for a density current in an unstratified environment. Of course, environments of MCSs are often not neutrally stratified. Furthermore, MCSs usually have a warm anomaly above the cold pool, which lowers pressure at the surface, and thereby acts to reduce MCS propagation speeds (e.g., Trier et al. 2005). The mid- to upper-level warm anomaly is not included in our calculations of C. Nevertheless, we evaluate how well C correlates with observed system movement for the BAMEX cases.

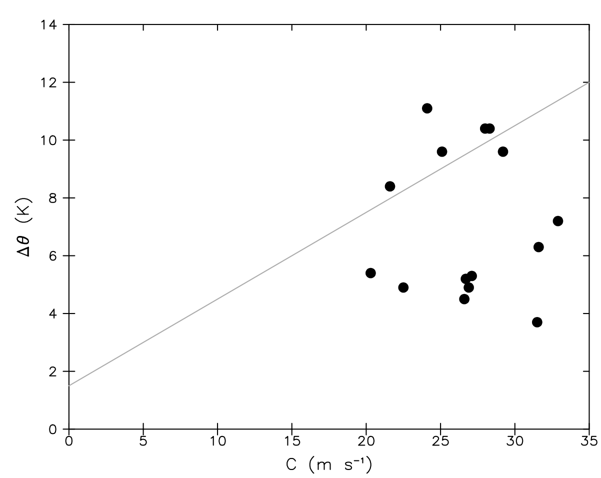

Fig. 4. Values of C and surface $\Delta\theta$. The grey line is the model-derived relationship from Stensrud et al. (2005).

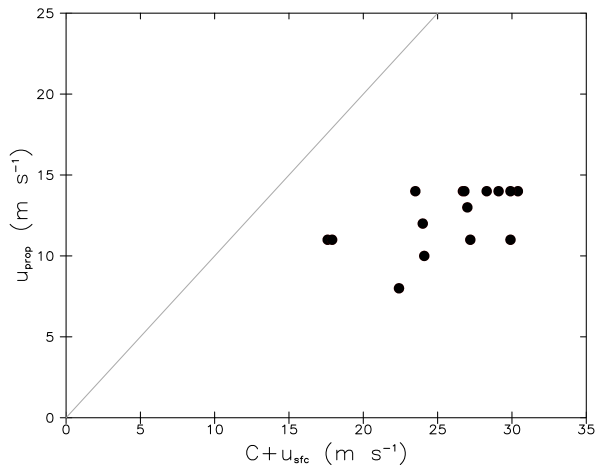

Fig. 5. Propagation speed of the convective systems (u_{prop}) compared with theoretical propagation speed based on density current dynamics ($C + u_{sfc}$).

Following Rotunno et al. (1988), we calculate the "ground-relative cold pool speed" as $C + u_{sfc}$, which is applicable to the cases studied herein because $C > \Delta U$ (where ΔU is the low- to mid-level shear, see Bryan et al. 2004 for calculations of ΔU for these cases). For most BAMEX cases, u_{sfc} is negative, and thus acts to retard system propagation.

Results indicate that ground-relative C systematically overpredicts propagation speed, usually by at least a factor of 2. We expected this to be the systematic bias, owing to the neglect of the mid- to upper-level warm anomaly. Unfortunately, we cannot extend the calculation of (1) to account for the warm anomaly aloft, as done by Trier et al. (2005), because the BAMEX soundings typically sampled only to z = 12 km, which is probably not deep enough. We are currently working with calculations of surface pressure across the MCS as a proxy for C; preliminary results (not shown) are encouraging for some cases, but indicate substantial differences for a few events. Detailed results will be reported in a future paper.

5. CONCLUSIONS

We are continuing to investigate the processes that lead to deep (H > 3 km) and intense (C > 20 m s^{-1}) cold pools. At this time, we feel the analyses are accurate, and that they point to conditions that have not been studied in depth in previous numerical studies. For example, elevated near-neutral layers were common during BAMEX. The significance of such layers is not well understood.

Furthermore, the presence of environmental stable layers near the surface is another common feature that deserves further study. Many of the BAMEX cases were nocturnal, wherein radiative cooling created inversions at the surface in the environment; such near-surface stable layers were shallow, and may not have played a significant role. However, other cases occurred on the northern side of warm fronts (or quasi-stationary fronts); in these cases, the near-surface stable layers were much deeper (> 1 km).

It is noteworthy that deep, intense cold pools can be created in spite of these deep surface-based stable layers. Analyses of equivalent potential temperature (θ_e, not shown) reveal that mid-level low θ_e air *does* penetrate to the surface in such cases, indicating that downdrafts *do* reach the surface, contrary to conventional wisdom (as expressed, for example, in Jorgensen et al. 2004). It is possible that elevated dry adiabatic layers are crucial in such environments, because they can lead to elevated layers of strongly negative buoyancy (e.g., Fig. 3). We are currently conducting idealized numerical simulations to evaluate these ideas.

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REFERENCES

Bryan, G., D. Ahijevych, C. Davis, M. Weisman, and R. Przybylinski, 2004: An assessment of convective system structure, cold pool properties, and environmental shear using observations from BAMEX. Preprints, *22nd Conf. on Severe Local Storms*, Hyannis, MA, Amer. Meteor. Soc., CD-ROM, 4.2.

Bukovsky, M. S., J. S. Kain, and M. E. Baldwin, 2005: Bowing convective systems in popular operational models: Are they for real? Preprints, *21st Conf. Weather Analysis and Forecasting / 17th Conf. Numerical Weather Prediction*, Washington, DC, Amer. Meteor. Soc., CD-ROM, 2A.1.

Evans, J. S., and C. A. Doswell III, 2001: Examination of derecho environments using proximity soundings. *Wea. Forecasting,* **16,** 329-342.

Fovell, R. G., and Y. Ogura, 1989: Effect of vertical wind shear on numerically simulated multicell storm structure. *J. Atmos. Sci.,* **46,** 3144-3176.

Jorgensen, D. P., H. V. Murphey, and R. M. Wakimoto, 2004: Rear-inflow evolution in a non-severe bow-echo observed by airborne Doppler radar during BAMEX. Preprints, *22nd Conf. on Severe Local Storms*, Hyannis, MA, Amer. Meteor. Soc., CD-ROM, 4.6.

Parker, M. D., and R. H. Johnson, 2004: Structures and dynamics of quasi-2D mesoscale convective systems. *J. Atmos. Sci.,* **61,** 545-567.

Rotunno, R., J. B. Klemp, and M. L. Weisman, 1988: A theory for strong, long-lived squall lines. *J. Atmos. Sci.,* **45**, 463–485.

Stensrud, D. J., M. C. Coniglio, R. P. Davies-Jones, and J. S. Evans, 2005: Comments on " 'A theory for strong long-lived squall lines' revisited." *J. Atmos. Sci.,* in press.

Szeto, K. K., and H.-R. Cho, 1994: A numerical investigation of squall lines. Part II: The mechanics of evolution. *J. Atmos. Sci.,* **51,** 425-433.

Thorpe, A. J., M. J. Miller, and M. W. Moncrieff, 1982: Two-dimensional convection in non-constant shear: A model of midlatitude squall lines. *Quart. J. Roy. Meteor. Soc.,* **108,** 739-762.

Trier, S. B., W. C. Skamarock, and M. A. LeMone, 1997: Structure and evolution of the 22 February 1993 TOGA COARE squall line: Organization mechanisms inferred from numerical simulation. *J. Atmos. Sci.,* **54,** 386-407.

——, C. A. Davis, D. A. Ahijevych, and M. L. Weisman, 2005: Mechanisms supporting long-lived episodes of propagating nocturnal convection within a 7-day WRF Model simulation. Submitted to *J. Atmos. Sci.*