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CONVECTION AND APPALACHIAN COLD-AIR DAMMING

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1. INTRODUCTION

Cold-air damming (CAD) is a common occurrence along the eastern slopes of the Appalachian Mountains in the southeastern US. Although there are multiple classifications of CAD (e.g., Bailey et al. 2003), this typically occurs when relatively cold air is driven southward initially in the form of a "backdoor" cold front (e.g., Carr 1951) and undergoes geostrophic adjustment with the increasing effect of the Coriolis force. Consequently, the flow of cold air is redirected toward the mountains and becomes blocked by the mountain barrier to form a shallow cold dome (e.g., Bell and Bosart 1988). As the cross-barrier force balance adjusts towards geostrophy, a low-level mountain-parallel jet forms and serves to help maintain the cold dome, driving the cold air farther southward (e.g., Forbes et al. 1987). This cold dome can extend as far southward as central Georgia (e.g., Fig. 1) and persist for several days before erosion occurs.

While cold season CAD brings many challenges to winter weather forecasting (e.g., Keeter et al. 1995), there is additional concern among operational forecasters with the role of CAD (including the warm season) in convective development. Although the cold dome stabilizes the lower-troposphere, the periphery of the CAD dome, or "wedge front", has been observed to trigger convective development (e.g., Fig. 1). When ambient moisture and instability are sufficient for convection to develop near the wedge front, the shear environment of the cold dome has been hypothesized to enhance the possibility of severe convection. The objectives of this research are to clarify and quantify the CAD cold dome influence on convection and the convective environment. Specifically, our goal is to isolate conditions in which the presence of CAD sufficiently alters convective storm structure and intensity. We hypothesize that the CAD cold dome makes an appreciable difference with convective intensity and behavior.

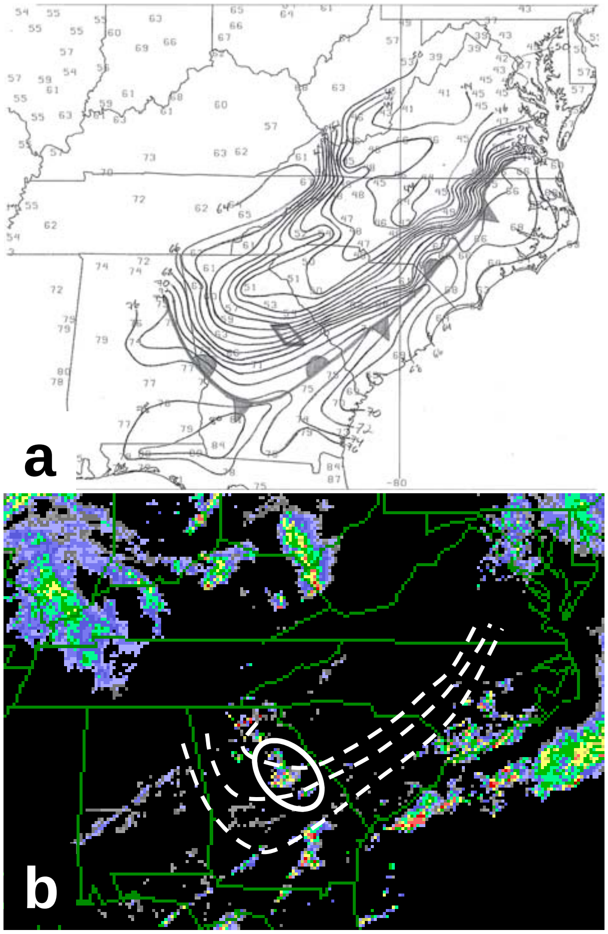

Figure 1. (a) Manual surface temperature (˚F) and frontal analysis at 2300Z 20 March 2003 and (b) radar composite reflectivity at 0000Z 21 March 2003 (bottom). Dashed white lines denote approximate location of temperature gradient along CAD dome periphery and white oval outlines developing convection.

2. DATA AND METHODS

In order to successfully isolate the effects of CAD and appropriately test the hypothesis, the following steps were taken: (1) identify cases of active convection along the CAD dome periphery from a comprehensive database of CAD event days, (2) isolate the most representative cases, and (3) use real case data to initialize model simulations for testing.

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2.1 Case identification

The process of identifying cases of active convection along the wedge front involved detailed criteria in multiple fields commonly analyzed in operational forecasting with the intention of maintaining the applicability of the research to the forecasting environment. An objective definition of “wedge-front convection” (WFC) was used to assemble a dataset of active WFC cases from specific spatial, temporal, and intensity requirements from temperature, radar, and reanalysis data associated with past CAD events. The CAD events used to determine WFC cases were compiled from (i) a list generated from the previous research of Tom Green, Wendy Sellers, and Chris Bailey, (ii) a list generated by a CAD algorithm from the NWS WFO in Columbia, SC (CAE), and (iii) from additional cases suggested by NWS forecasters. Together the lists provided 241 total days of CAD that could be analyzed for WFC with resources of consistent data, spanning from 01 April 2001 to 15 June 2007 (approximately 6 years).

Once a dataset of active WFC cases was assembled, the cases were analyzed for representativeness in (i) cold dome strength, (ii) severity of convection, and (iii) amount of ambient moisture and instability. Data from a case determined to be best representative of convection associated with a relatively strong cold dome was used to initialize numerical simulations for testing.

2.2 Numerical simulations

When properly conducted, numerical simulation comparisons can provide an efficient method for isolating key physical processes in various atmospheric phenomena and can serve as robust tests of scientific hypotheses. Successful isolation of the CAD cold dome’s effect on the lower-tropospheric convective environment was achieved through a modeling experiment in which version 2.2 of the Weather Research and Forecasting (WRF) model was initialized with North American Regional Reanalysis (NARR) gridded data from a representative real case. A simulation of a CAD cold dome serves as the control run (CAD run) for testing against, and a second simulation with the same initial conditions as the CAD run, but with the Appalachian mountains removed serves as the experimental run (NoCAD run). Removal of the mountains, while keeping all other atmospheric features nearly identical to the CAD run, resulted in a similar pattern evolution but without the presence of CAD. An analysis of the differences in the lower-tropospheric environment between the CAD and NoCAD runs was conducted to isolate the effect of the actual cold dome presence in the model.

3. CASE REPRESENTATIVENESS

Results from the identification process indicate that there were 17 CAD events identified with active wedge-front convection. Of these CAD events, there were 24 active WFC days, which is approximately 10% of the total CAD days.

After the analysis of CAD cold dome strength, 6 active WFC days were found to be associated with relatively weak CAD cold domes, 9 with moderate domes, and 9 with strong domes. Archived storm reports from the Storm Prediction Center were analyzed to see if any matched the time and location with identified wedge-front convection on radar. Upon completion of the analysis, 6 out of 17 WFC events included some severe convection (approximately one third of the events). Of the 6 severe events, 4 were associated with relatively strong CAD domes. Based on surfaced-based CAPE values, the WFC occurrences were separated into bins of relatively high or low CAPE values. A case occurring on 20 March, 2003 was overall the best example of strong CAD dome convection (Fig. 1), and makes it appropriate for initializing simulations.

4. MODEL EXPERIMENTS

4.1 Initial simulations

Simulations were initially performed to analyze the effect of the CAD dome on the lower troposphere in a relatively large-scale environment. Horizontal gridspacing was kept at 12 km and the Kain-Fritsch convective parameterization scheme was used to account for sub-gridscale convective processes. NARR gridded data from the real case of 20 March, 2003 were used to initialize the CAD run, since it was representative of convective development associated with a wedge front along a relatively strong and definite CAD cold dome. The simulations were run for 72 forecast hours from before CAD started to occur (0600Z 18 March, 2003) until after convection was active along the wedge front (0600Z 21 March, 2003).

4.1.1 Control run (unmodified terrain)

The control CAD simulation successfully represented convection along the wedge front (Fig. 2a). Much of the total convective precipitation occurred near the location of the relatively strong temperature gradient along the cold dome periphery. The development of a mountain-parallel jet led to enhanced frontogenesis and convergence along and near the cold dome periphery shortly before significant convective precipitation amounts were present (not shown). The cold dome was analyzed to be in a region of limited moisture and instability (with higher amounts near the periphery relative to the dome interior) and vertical wind shear and 0-1-km storm relative helicity (SRH) values capable of producing strong to severe convection (not shown).

4.1.2 Experimental run (flattened terrain)

When compared to the CAD run, the NoCAD run had significant convection closer to the Atlantic coastline (Fig. 2b), suggesting that CAD influenced the preferred region for convective development to be located more inland. There was increased moisture and instability and decreased 0-1-km SRH values in the NoCAD run across the same geographical region where the cold dome was analyzed in the CAD run (not shown). Difference plots of 0-1-km SRH between the two runs indicate ~600 m^2/s^2 higher values in the CAD dome region (not shown).

While these simulations suggest that the cold dome alters the lower-tropospheric shear and thermodynamic environment and that the region near the wedge front serves as a lifting mechanism capable of triggering convective development, the specific influence of the wedge front on convective character and intensity cannot be determined from the coarse 12-km grid used to this point. Therefore, nested domains with finer spatial and temporal resolution were utilized in order to explicitly resolve convective development and behavior. This will allow determination of the extent to which convective storms were able to draw on the helicity-rich air found in the vicinity of the wedge front. Also, comparison of convective cells in these high-resolution simulations will reveal whether storms were more likely to exhibit rotation when forming in the vicinity of the cold dome.

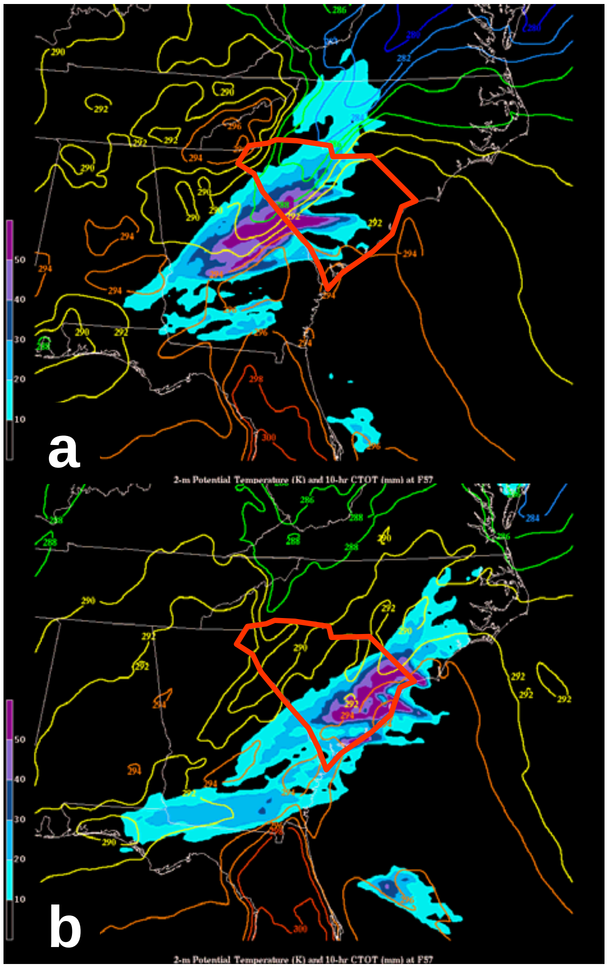

Figure 2. 2-m potential temperature (contours, interval 2 K with cooler colors representing lower values) and 10-hr convective precipitation amounts (fill, interval 10 mm starting at 10 mm) ending at 1200Z 20 March 2003 (forecast hour 57) for (a) the CAD run and (b) NoCAD run. South Carolina is outlined in red to provide a visual reference frame for the location of convective precipitation amounts.

4.2 Convective-scale simulations

Additional simulations were performed at 1.3-km horizontal gridspacing and a 5-minute output interval to allow for analysis at the convective scale and capture the behavior and evolution of convective storm development.

4.2.1 Control run (unmodified terrain)

The control run (hereafter referred to as “CAD-CS run” for the convective scale) used the initial 12-km domain as the outermost domain and included two nested domains at 4-km and 1.3-km to maintain a 3:1 gridspacing ratio between domains. The innermost domain at 1.3-km gridspacing was centered over the region of significant convective precipitation analyzed in the initial CAD run, therefore this domain was used for the convective scale analysis.

Composite reflectivity values indicated a significant region of convection across central Georgia and South Carolina (Fig. 3a). Convective development initially became apparent along the warm side of the wedge front at 0505Z 20 March, 2003, while subsequent convective development occurred along a region of enhanced frontogenesis and convergence located along the eastern extent of the mountain-parallel jet as it developed within the cold dome and pushed farther southward. The convection had discrete cellular structure and some cells split into right- and left-movers with the right-movers having increased longevity – a behavior common in shear environments with increased low-level positive SRH values. After several hours of development the convective region formed into a squall-line and propagated eastward (not shown).

4.2.2 Experimental run (flattened terrain)

The experimental run (hereafter referred to as "NoCAD-CS run" for the convective scale) employed the same domain gridspacing and initializations as the CAD-CS run, but had the mountains removed to simulate the same atmosphere without the effect of CAD (analogous to the initial NoCAD run). The nested domains were centered more over the South Carolina coastline to allow for analysis in the region of significant convective precipitation analyzed in the initial NoCAD run.

A significant region of convective development was analyzed in the composite reflectivity where initial development occurred about an hour after what was analyzed in the CAD-CS run and in a location over 200 km farther to the northeast (in central South Carolina, Fig. 3b). Without the presence of the cold dome, the convection developed initially in a more linear structure (less discrete) and did not appear to involve cell splits. The convective region also formed into a squall-line (with a more rapid transition than in the CAD-CS run) which propagated eastward.

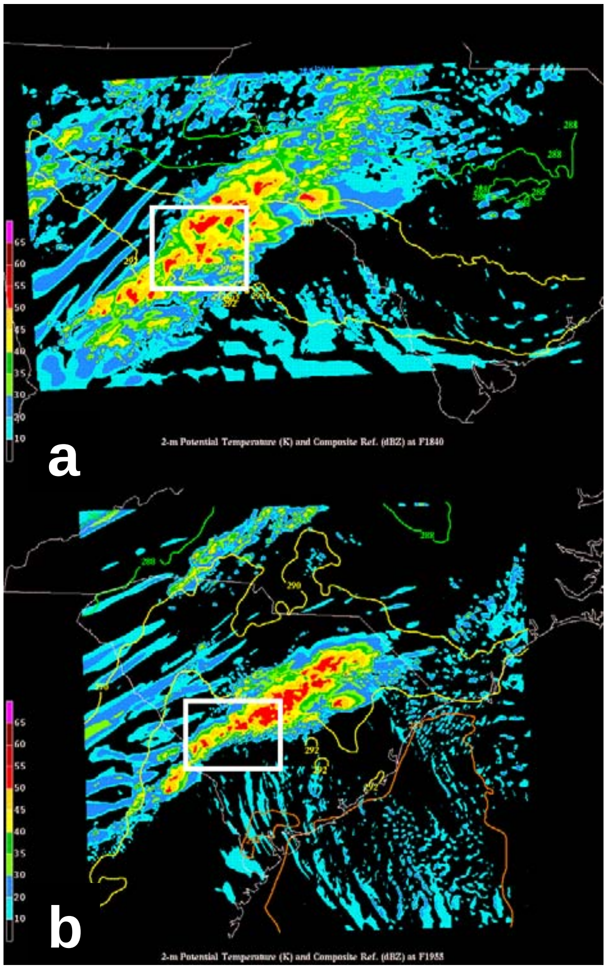

Figure 3. 2-m potential temperature (contours, interval 2 K with cooler colors representing lower values) and composite reflectivity (dBZ) across central GA and SC from CAD-CS run at 0640Z 20 March, 2003 (a) and across central SC from NoCAD-CS run at 0755Z 20 March, 2003 (b). White rectangles outline areas shown in Fig. 3a and 3b respectively.

4.2.3 Averaged model hodographs

In order to analyze the shear environment in which the convective development occurred, averaged hodographs were calculated across various locations and times in the simulated atmosphere. Figure 4 shows the average hodographs along the region where convection occurred at a time immediately prior to initial development in both convective-scale runs. While the NoCAD-CS run did have some positive low-level SRH present, the CAD-CS run had nearly twice as much low-level SRH present, suggesting more environmental streamwise vorticity available for tilting into the vertical by any developing convective updrafts.

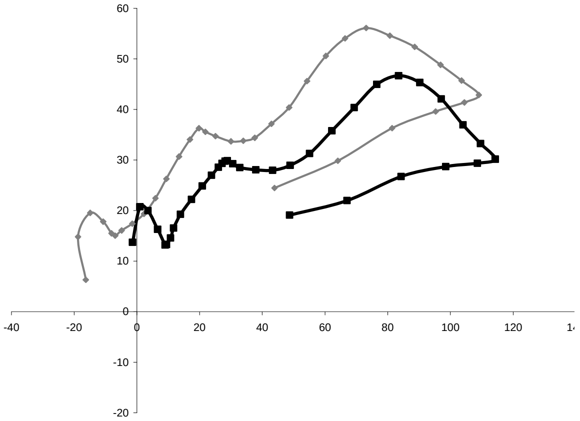

Figure 4. Averaged hodographs (kts) for the CAD-CS run (grey) and NoCAD-CS run (black). The hodographs extend from the closest plotted pressure level to the surface (lower left endpoints) to 125 mb (right endpoints).

4.2.4 Updraft rotation

A cross-sectional analysis of a right-moving cell following a split in the CAD-CS run showed the presence of counterrotating vertical vortex pairs, with the cyclonic vortex co-located with the storm's updraft (not shown) – also suggesting the influence of streamwise vorticity on the developing convection.

The product of vertical velocity and vertical vorticity within the convection was analyzed across multiple cells during development in both convective-scale runs and indicated rotating updrafts (Fig. 5). Frequencies of significant updraft rotation across grid points in similar geographical areas for both convective-scale simulations are currently being calculated to better quantify the convective behavior and intensity between the runs. Preliminary results suggest that the significant convection in the NoCAD-CS run reaches updraft rotations of moderate intensity more frequently than in the CAD-CS run. Vertical velocities within the convection overall appear to be stronger in the NoCAD-CS as well. The increased updraft strength appears to be attributable to the higher moisture and instability values in the NoCAD environment.

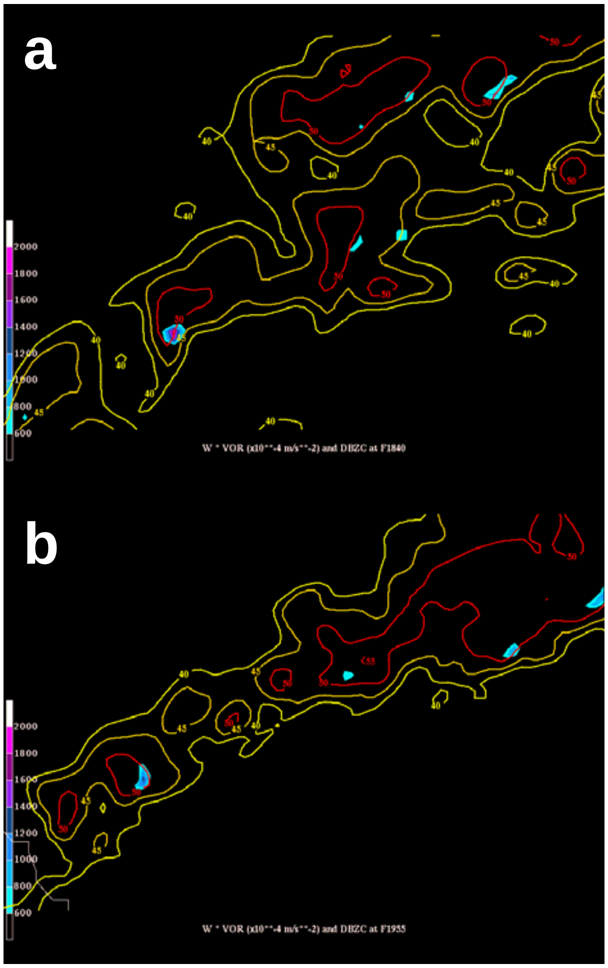

Figure 5. Convective cells outlined by white rectangles in (a) Figure 3a and (b) Figure 3b. Updraft rotation (fill, interval 200 x 10^{-4} m/s^2 at values greater than or equal to 600 x 10^{-4} m/s^2) at the 700 mb level and composite reflectivity (contours, interval 5 dBZ at values greater than or equal to 40 dBZ).

5. CONCLUSIONS

After identifying cases of active WFC and conducting an analysis of representativeness, the 20 March, 2003 case was found to be representative of convection associated with a relatively strong and well defined CAD cold dome. Initial CAD and NoCAD WRF simulations initialized with NARR data from this case suggested that the CAD cold dome primarily stabilized the environment (with higher moisture and instability amounts along the periphery relative to the dome interior) and increased low-level SRH. The development of a mountain-parallel jet led to an area of enhanced frontogenesis and convergence near the wedge front and serves as a lifting mechanism and preferred region for convective development.

Additional simulations on the convective scale indicated that convection developed near the wedge front in a region of increased low-level SRH, whereas the storms without the influence of a CAD cold dome developed in a region of increased moisture and instability. Although both simulated regions of convection eventually evolved into squall lines, the pre-squall-line period of development near the wedge front included discrete cell structures and cell splits with increased longevity, while a more linear reflectivity structure with less discreteness occurred in the absence of the wedge front. Rotating updrafts of moderate intensity were analyzed in the convection for both convective-scale runs, indicating the tilting of environmental streamwise vorticity into the vertical.

Quantifications of convective character and intensity are currently being conducted in the research to properly compare the convective regions between the CAD-CS and NoCAD-CS runs and isolate the role of the wedge front on the convection. Preliminary results suggest that although significant updraft rotation within the convection was present in both runs, the frequency of moderately strong updraft rotation was notably higher without the presence of CAD. While more low-level environmental streamwise vorticity is available for tilting into the vertical by convection along the CAD cold dome periphery, the convection without the presence of CAD appears to have more overall updraft rotation likely due to the increased moisture and instability.

6. ACKNOWLEDGEMENTS

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