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COLD-AIR DAMMING EROSION: PHYSICAL MECHANISMS, SYNOPTIC SETTINGS, AND MODEL REPRESENTATION

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1. INTRODUCTION

When statically stable flows encounter an orographic barrier in a rotating system, upwind ridging and downwind troughing will develop, in part as a manifestation of the geostrophic adjustment process (e.g., Bell and Bosart 1988; Lackmann and Overland 1989). For the Appalachian Mountains, the result of this adjustment process is a dome of cool, stable air east of the mountains that is often accompanied by low clouds, fog, drizzle, and occasional wintry precipitation. This phenomenon and the characteristic "U"-shaped isobar configuration accompanying it have come to be known as "cold-air damming" (CAD, e.g., Richwien 1980, Bell and Bosart 1988). The relative coldness of the CAD is the result of (i) along-barrier cold advection, (ii) orographic ascent, and, when sufficient moisture and lift are present, (iii) evaporative cooling and sub-cloud sheltering from insolation. Fritsch et al. (1992) note that clouds and precipitation can play a significant role in the strengthening of CAD through evaporative cooling; near-surface evaporational cooling increases static stability, the degree of orographic blocking, and the strength of CAD.

CAD can have a significant impact on the weather between the crest of the Appalachian Mountains and the coastal plain. The difference in temperature between the damming region and the coast can exceed 20°C during strong CAD events (Bell and Bosart, 1988). During the cold season, this can mean the difference between rain and freezing or frozen precipitation.

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The experience of operational weather forecasters in the Appalachian damming region has shown that numerical model guidance during the *erosion* of cold-air damming is not reliable; there is a characteristic bias towards the premature erosion of the CAD cold dome in model forecasts, leading to predictions of the cessation of CAD sensible weather (Keeter et al. 1995).

Careful study of the physical mechanisms responsible for CAD erosion in various synoptic settings has only recently been undertaken. The research objectives presented here address this problem in three distinct ways: (i) we review the primary physical mechanisms of CAD erosion, (ii) we document the synoptic settings that most commonly accompany CAD erosion, and (iii) we summarize the results of model sensitivity studies that provide the initial inquiry into the question of which physical processes are responsible for the poor NWP performance during CAD-erosion.

2. PHYSICAL CAD-EROSION PROCESSES

Considering the surface-based cold pool during a damming event, it is clear that the structural integrity of the cold dome depends on the strength of the inversion separating the cold topographically trapped air from the free atmosphere above. At the conclusion of a CAD event, this inversion is eradicated and mixing takes place, removing the stable topographically trapped air mass. Interpreted in this fashion, the bulk Richardson number evaluated across the inversion provides a convenient means of monitoring the vitality of the inversion layer, and interpreting the processes that may act to weaken it.

$$R_{iB} = \frac{\dfrac{g\,\Delta\theta_v}{\theta_v}}{\dfrac{(\Delta u)^2 + (\Delta v)^2}{\Delta z}} \qquad (1)$$

The numerator in (1) is proportional to the strength of the capping inversion, and the denominator is the strength of the wind shear across the inversion layer. Large shear or a weak inversion lead to a small Richardson number and a greater chance of entrainment and turbulent mixing across the inversion. Such mixing is ultimately responsible for the eradication of the cold dome.

Examination of observational data during the erosion period of many CAD events over the past several years, and analysis of numerical and observational case studies of CAD demise has elucidated the mechanisms primarily responsible for CAD erosion. These five mechanisms are not entirely independent of one another, and include (i.) differential thermal advection, (ii.) solar heating, (iii.) lower-tropospheric divergence, and (iv.) shear-induced mixing (entrainment) across the top of the cold dome. A fifth mechanism that relates to several of these processes is the advance of the coastal/warm front that often marks the eastern/southern terminus of the CAD cold dome.

2.1. Differential thermal advection

Operational forecasters in the Appalachian damming region have long recognized that warm advection aloft in conjunction with shallow cold advection near the surface serves to strengthen the capping inversion during CAD events. Warm advection aloft can also promote ascent, providing clouds and precipitation that can further stabilize and protect the CAD cold dome. However, it is less widely recognized that *cold advection aloft frequently serves to weaken the inversion during CAD erosion*. Furthermore, cold advection favors quasigeostrophic descent, aiding in the dissipation of cloud cover and in some instances allowing solar heating to further weaken the capping inversion. CAD erosion cases that are dominated by cold advection aloft are characterized by "top-down" erosion of the cold dome.

Cold advection aloft can develop in the wake of a coastal cyclone, following a cold-frontal passage, or during the passage of a cold-front aloft (CFA). A distinguishing characteristic in cases in which erosion is dominated by differential thermal advection is that cooling above the inversion is more pronounced than warming below.

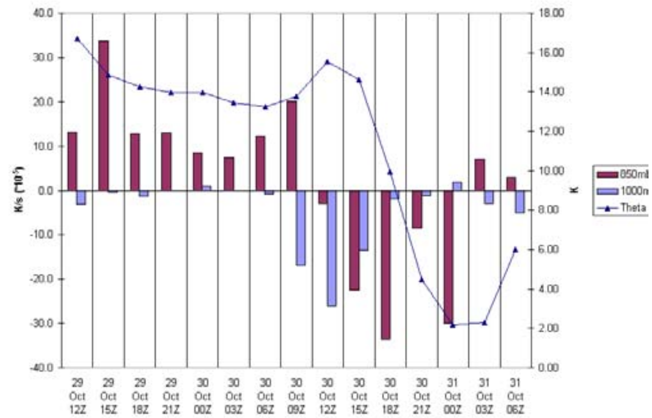

Figure 1. Time series of inversion strength (solid line plotted with scale on right ordinate), 1000-mb thermal advection (blue bars), and 850-mb thermal advection (maroon bars) for the CAD-erosion event of 30 October 2002.

Figure 1 shows an example in which the strength of the inversion (given by the solid line) at Greensboro, NC in a model-simulated CAD event initially increases with warm advection aloft and cold advection near the surface, but later decreases rapidly as cold advection commences at the 850-mb level (above the inversion).

2.2. Solar heating

Earlier studies demonstrate that the presence or absence of cloud cover is a major factor in dictating the magnitude of sensible weather impact during CAD events (Bailey et al. 2003). However, when cloud cover begins to erode, solar heating can act to warm the near-surface cold dome, thereby weakening the inversion and promoting mixing. These "bottom-up" erosion cases are most common during spring, summer, and fall, and are obviously promoted when cloud cover is broken or absent. In these cases, it is warming below the inversion, rather than cooling above, that is the primary weakening mechanism.

An idealized depiction of how rawinsonde soundings might appear in the center of the damming region is provided in Fig. 2. Here, we see that temperatures and dew points aloft do not exhibit much change, but lower-tropospheric drying allows solar heating to warm the surface.

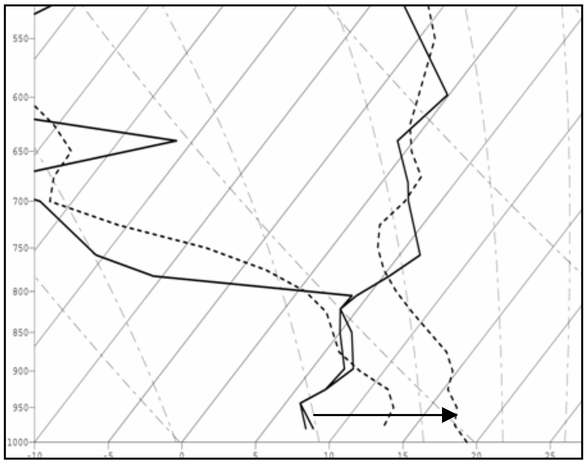

Figure 2. Idealized before and after sequence of soundings during a CAD erosion event. The solid lines depict temperature and dew point (in skew-T format) during a damming event, while the dashed lines represent these quantities at a later time, after solar heating has acted to warm the lower troposphere.

2.3. Lower-tropospheric divergence

During the mature stage of a cold-air damming event, it is typical for strong northeasterly winds to develop in the southern damming region with lighter wind to the north in Virginia. This leads to a general pattern of velocity divergence within the cold dome, as the cool, stable air "drains" away to the southwest. If the parent high (cold air source) to the north is no longer in a favorable position to replenish the cold dome, this divergence serves to reduce the depth of the cold air, making the cold dome more susceptible to erosion. Also, the divergence implies subsidence through continuity, which can help to dry the dome and allow solar radiation to penetrate to the surface.

In other cases, for example when a strong cyclone develops along or moves up the East Coast, acceleration of the cold-dome air towards the region of rapid pressure falls will also contribute to divergence and a reduction in cold-dome depth.

2.4. Shear-induced mixing

As the inversion weakens due to other mechanisms, eventually mixing may take place and result in cold dome erosion. However, in some instances the Richardson number reduction is more the result of increasing shear across the inversion layer rather than a weakening of the inversion. For example, in some settings a southerly low-level jet will develop above the CAD layer in association with a cyclone to the west or northwest of the damming region. At the periphery of the cold dome, the shear may become sufficiently large to result in entrainment and mixing, and erosion of the cold dome. This is another form of "top-down" CAD erosion.

2.5. Advance of coastal/warm fronts

Although frontal advance is related to all of the factors listed above, it is useful to monitor CAD erosion in terms of the movement of frontal boundaries marking the edge of the cold dome. For example, when pressures fall to the north of the damming region due to the approach of a synoptic cyclone, divergence within the cold dome may enhance the inland penetration of the coastal front, as evident in the example shown in Fig. 3.

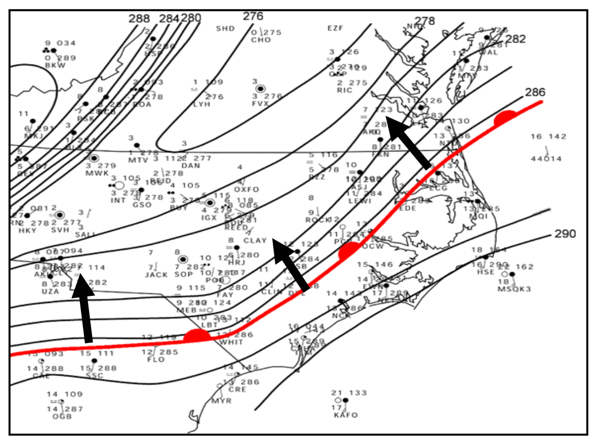

Figure 3. Example of the inland movement of a coastal/warm front during the demise of a cold-air damming event from February 2000. Details of this case are found in Brennan et al. 2003.

3. SYNOPTIC SETTINGS OF CAD EROSION

Earlier studies (e.g., Bailey et al. 2003) have shown that there are several distinct "flavors" of cold-air damming, and that these events can be stratified according to the relative importance of diabatic processes (e.g., evaporational cooling) to synoptic-scale forcing (e.g., the strength and location of the "parent high"). However, this research also demonstrated that the processes leading to the erosion and ultimate demise of the damming event are independent of the CAD onset mechanisms. Stanton (2003) examined 90 cases of “classical” cold-air damming and was able to identify four distinct synoptic patterns that are characteristically associated with CAD erosion. These scenarios are dubbed (i.) coastal cyclone, (ii.) cold-frontal passage, (iii.) residual cold pool, and (iv.) northwestern low. Below we present composites of each of these categories along with a discussion of the physical erosion mechanisms most likely to be active in each setting.

3.1. Coastal cyclone

In approximately 27% of the CAD erosion events, the synoptic setting featured a cyclone developing or redeveloping along the coast, as depicted in the composite shown below. In these situations, cold advection aloft and near-surface divergence were typically observed as the primary erosion mechanisms. During cases of weak cyclogenesis, the CAD dome was maintained despite an unfavorable synoptic environment. For example, during an event on 30 October 2002, the cold dome was observed shifting towards the coast in response to pressure falls associated with a cyclone developing there (not shown).

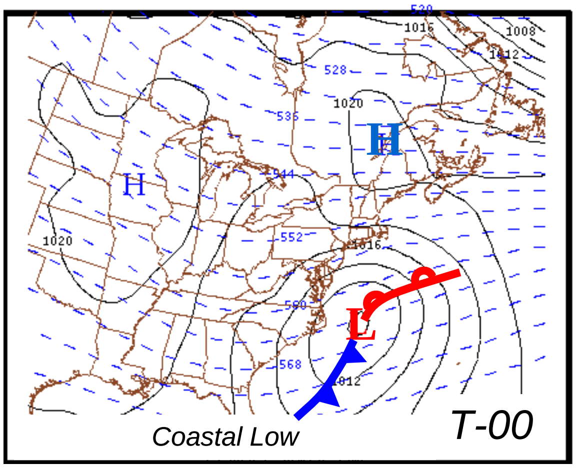

Figure 4. Composite sea-level pressure (solid black, contour interval 2 mb) and 500-mb Geopotential height (dashed blue, contour interval 6 dam) for the coastal low erosion scenario.

3.2 Cold-frontal passage

During approximately 16% of the CAD erosion events studied, the cold dome demise was accompanied by the passage of a synoptic cold front.

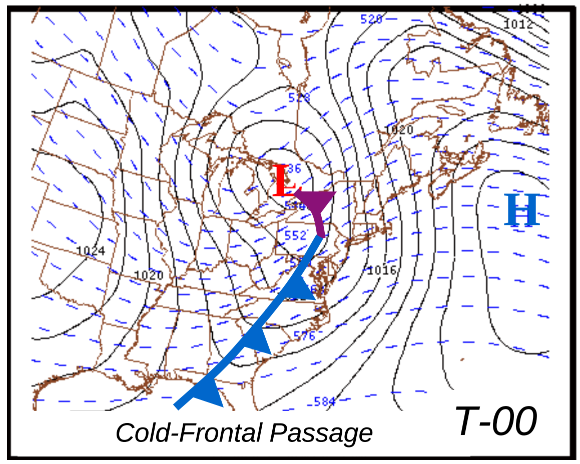

Figure 5. As in Fig. 4, except for cold-frontal passage erosion scenario.

In these situations, cold advection aloft, downslope flow east of the Appalachian Mountains, and subsidence were typically observed. The subsidence led to drying and dissipation of cloud cover, allowing solar heating to contribute to CAD demise in some cases.

3.3 Residual cold pool

In approximately 27% of the CAD-erosion events studied, there was no prominent synoptic feature in the vicinity at the time of CAD demise. Rather, the parent anticyclone typically weakened and moved offshore, leaving a residual pool of cool, dry air over the damming region. In these instances, solar heating was a primary factor in eliminating the CAD inversion, as there was no strong thermal advection signature.

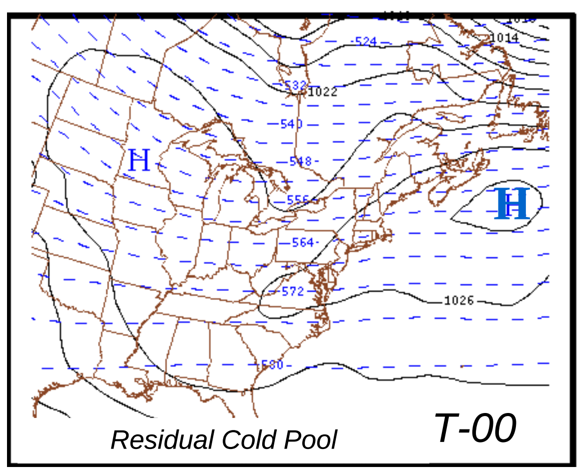

Figure 6. As in Fig. 4, except for residual cold pool erosion scenario.

3.4. Northwestern low

The large-scale synoptic pattern accompanying the northwest low erosion scenario is similar to that for the cold-frontal passage, with the notable difference that the CAD erosion was complete prior to the arrival of the cold front in the damming region. These events comprised approximately 29% of those studied in the initial climatology of Stanton (2003).

Candidate erosion processes in these events include shear-induced mixing at the inversion, near-surface divergence, and solar heating. However, in some instances where a CFA moves ahead of the surface cold front, it is possible that cold advection aloft could also contribute to the CAD demise.

The northwest low perhaps represents the biggest challenge to operational NWP models, which frequently erode the cold dome prematurely in these situations. Thus, the model forecast will indicate sensible weather conditions typical of the warm sector, when in fact low clouds, fog, drizzle, and cool temperatures will often prevail for many hours after the model has indicated CAD demise. We speculate that the difficulties arise in part due to the challenge of modeling solar radiation interactions with shallow cloud cover within the cold dome.

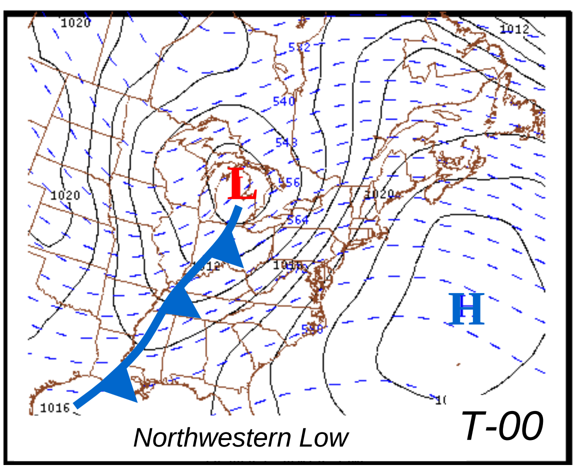

Figure 7. As in Fig. 4, except for northwest low erosion scenario.

4. MODEL REPRESENTATION

Of the physical erosion mechanisms discussed in section 2, we expect that operational NWP models should have a realistic depiction of synoptic-scale cold advection. This means that for events in which the erosion is dominated by cold advection aloft, one would expect that the model would provide a reasonably accurate solution. This suggests that the cold-frontal erosion scenario should generally be well-handled, provided that the model has an accurate depiction of the frontal timing and strength. For the coastal low erosion scenario, the model would do well as long as there was an accurate handle on the coastal cyclone itself.

A more difficult process for models to accurately represent is the interaction between solar heating and the shallow cloud cover that often characterizes decaying CAD events. Here, the ability of the model to accurately time the CAD demise will depend on model representation of a shallow stratus or stratocumulus layer. Experience with the NCEP Eta model has shown that this model tends to overestimate surface heating in these situations, bringing the CAD event to a premature demise (Stanton 2003). Thus, the residual cold pool and northwest low erosion scenarios may exhibit large model error. Furthermore, events that tend to end as cold-frontal passage scenarios in the real atmosphere may appear to end as northwest low scenarios in the model atmosphere.

5. CONCLUSIONS AND FUTURE WORK

In this preprint we have summarized results from both climatological and case studies of Appalachian CAD erosion. Five CAD erosion mechanisms were discussed: cold-advection aloft, solar heating, lower-tropospheric divergence, entrainment across the CAD inversion, and the advance of coastal or warm frontal boundaries.

Examination of many CAD cases revealed that four distinct synoptic settings accompany CAD erosion. Composites of these scenarios suggest that each erosion setting is preferentially accompanied by certain erosion mechanisms. Some of these mechanisms are well-handed by operational NWP models, while others are expected to be more problematic. Cold advection/cold frontal passage is generally accurately predicted by the models, while the representation of solar heating in the presence of shallow cloud cover presents a greater challenge to NWP models.

Detailed case studies of a coastal low even and a northwest low event are presented by Stanton (2003). These case studies feature model experiments designed to pinpoint the sensitivity of model solutions to various physical parameterizations. The following is a summary these findings:

• In an October 2002 coastal low erosion event, the MM5 model eroded the event prematurely in part because of too much solar radiation reaching the surface in the model (relative to actual surface radiation measurements). Also, cold advection aloft began too early in the model.

• Experiments in which the cloud albedo was altered demonstrated that although the erosion took place earlier in the low albedo experiment, this process could not fully explain the model error. The erosion was still premature in the high-albedo experiment.

• During a mature, well-established CAD event, forecasters should be skeptical of model forecasts of CAD erosion in the absence of strong cold advection aloft or clear- to partly-cloudy conditions.

• The problem of premature CAD erosion is highly sensitive to the choice of model PBL scheme. The Blackadar scheme produced the most accurate representation of CAD erosion during several case studies.

Future research on this problem is required to improve NWP guidance and more fully document the mechanics of CAD erosion. This will necessitate additional case studies, perhaps including warm season events and other erosion settings, particular cases with shallow cloud cover.

6. ACKNOWLEDGEMENTS

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